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Coalbed Methane Extraction: Detailed Study Report

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1. EXECUTIVE SUMMARY/INTRODUCTION

This report summarizes the information collected and analyzed by the U.S. Environmental Protection Agency (EPA) as part of a study of the coalbed methane (CBM) extraction industry. Currently, CBM discharges are not covered by an Effluent Limitation Guideline (ELG), but are regulated under Best Professional Judgment (BPJ) permits.

CBM is a form of natural gas that is found in coal seams and is extracted by drilling wells into the coal seams. Unlike extraction of conventional natural gas, CBM extraction requires the removal of groundwater to reduce the pressure in the coal seam, which allows CBM to flow to the surface through the well. This water must be managed and, in several states, is sometimes permitted for discharge directly or indirectly (via a publicly owned treatment works [POTW]) to surface waters.

CBM is currently produced in 15 basins[1] as shown in Table 1-1 (U.S. EPA, 2010a). Figure 1-1 illustrates the locations of these basins. The states in which direct or indirect discharges to surface waters are occurring are Alabama, Colorado, Illinois, Montana, Pennsylvania, West Virginia, Wyoming, and Virginia.

Table 1-1. Currently Producing CBM Basins and Locations

Basin	States
Appalachian	Virginia [a], West Virginia [a], Pennsylvania [a]
Black Warrior	Alabama [a]
Cahaba	Alabama [a]
Greater Green River	Wyoming [a]
Powder River Basin (PRB)	Montana [a], Wyoming [a]
Raton	Colorado [a], New Mexico
San Juan	New Mexico
Uinta-Piceance	Utah, Colorado
Anadarko	Oklahoma
Arkoma	Oklahoma, Arkansas
Cherokee/Forest City	Kansas
Arkla	Louisiana
Permian/Ft. Worth	Texas
Illinois	Illinois [a], Indiana
Wind River	Wyoming [a]

a – States that permit CBM produced water discharge to surface water or POTW.

[1] Basins are defined as large regions underlain by coalbeds with known CBM resources.

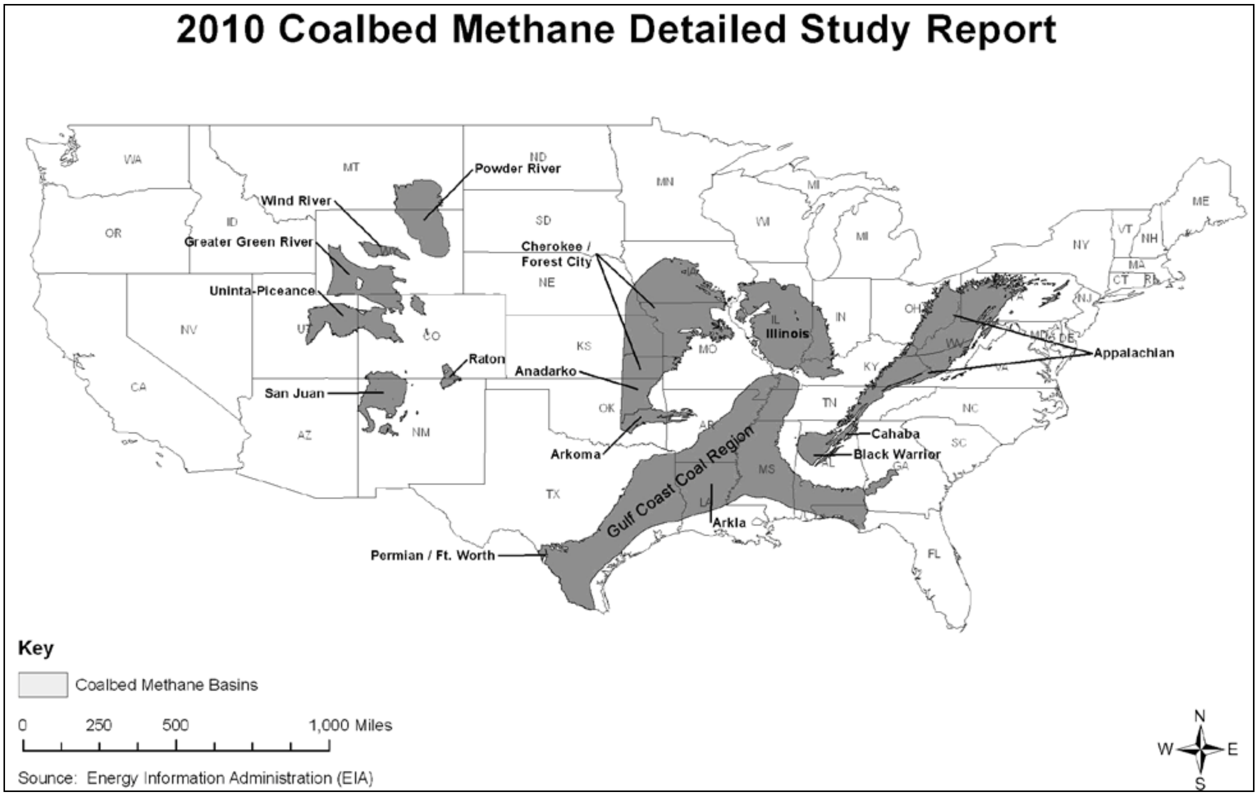


Figure 1-1. Locations of Currently Producing CBM Basins

EPA received comments during the 2005 annual review from citizens and environmental advocacy groups requesting development of a regulation. In 2005, EPA identified the CBM extraction industry as a candidate for a preliminary study (U.S. EPA, 2006).

For the 2006 annual review, began EPA collecting data on the number of active basins producing CBM and their produced water disposal practices. In 2007 EPA began a more detailed study of the CBM industry. EPA gathered additional information; including conducting numerous site visits to meet with stakeholders and observe a number of CBM produced water treatment technologies.

For this detailed study, EPA used a three-pronged approach to collect additional data on this industry: (1) meetings with stakeholders, (2) site visits, and (3) industry surveys—a national screener survey and a statistically sampled detailed survey.

EPA developed a technical and economic profile of the industry, which details information on CBM wastewater discharges, treatment technologies that are available to treat pollutants associated with CBM discharges (mostly total dissolved solids [TDS]), and the financial and economic characteristics of the industry.

Using survey responses and other data, EPA evaluated the following: the quality and quantity of produced water generated from CBM extraction; the available management, storage, treatment, and disposal options; and the potential environmental impacts of surface discharges. The findings from this detailed study are described in this report and include:

- Approximately 45 percent of all produced water is discharged to waters of the United States.
- Various pollutants such as sodium, calcium, and magnesium (used to calculate the sodium adsorption ratio [SAR]), total suspended solids (TSS), and metals (e.g., selenium, chromium) are present in discharges.
- Surface water discharges of produced water can increase stream volume, streambed erosion, suspended sediment, and salinity.
- Pollutants from CBM discharges may negatively affect fish populations over time.
- Surface impoundment and land application of produced waters may impact groundwater from infiltration and the concentration and/or bioaccumulation of CBM-associated pollutants.
- Advanced water treatment options are being used in the field in some operations to remove pollutants in produced water.
- Widely practiced zero discharge options may be available depending on well location.
- Although the recent downturn in the economy has negatively impacted the CBM industry, projections going forward appear more optimistic, with higher prices for gas predicted over the longer term.

2. DATA COLLECTION ACTIVITIES

EPA collected and evaluated information from numerous sources to support the development of the CBM Detailed Study. EPA used this data to develop an industry profile, characterize the wastewater and identify potential pollution control technologies, review the potential pollutant load reductions associated with certain treatment technologies, and review environmental impacts associated with discharges from this industry. This chapter discusses the following data collection activities:

- Meetings with industry and stakeholders (Section 2.1);
- Site visits, including the site selection process and the information collected (Section 2.2);
- Data collection to identify the universe of entities for a survey effort (Section 2.3);
- Industry survey activities, including a description of the questionnaires (Section 2.4); and
- Collection and review of National Pollutant Discharge Elimination System (NPDES) permits (Section 2.5).

Other data examined in this study include information from wastewater treatment equipment vendors, the U.S. Geological Survey (USGS), and literature and Internet searches on CBM processes, technologies, wastewaters, pollutants, and regulation. In addition, EPA considered information provided in public comments during the effluent guidelines planning process, as well as other contacts with interested stakeholders. EPA also used publicly available information from the U.S. Department of Energy's (U.S. DOE's) Energy Information Administration (EIA), various state oil and gas commission websites, Securities and Exchange Commission (SEC) filings by publicly held firms identified as producing CBM, the *Oil & Gas Journal*, and other information as cited in Chapter 3.

2.1 Stakeholder Outreach

For this detailed study, EPA conducted extensive stakeholder outreach in addition to an expansive site visit program to help identify key issues and concerns of industry and other stakeholders. The outreach goals for the detailed study included: (1) collecting information from stakeholders; (2) explaining the purpose for an industry survey and the process for approval and implementation of the survey; and (3) identifying and resolving issues as early as possible. This outreach helped facilitate the development of the questionnaire as comments and suggestions from industry and other stakeholders were incorporated into the survey design.

EPA met with a range of stakeholders (e.g., industry representatives; federal, state, and tribal representatives; public interest groups and landowners; and water treatment experts) to obtain the best available information on the industry and its CBM produced water management practices.

To initiate stakeholder involvement, EPA conducted seven teleconferences and 13 meetings in Washington, D.C. during 2007. Meeting participants included representatives from EPA and other federal, state, and tribal agencies (e.g., DOE, USGS, the U.S. Forest Service, and the U.S. Department of Interior); representatives from the affected industry; members of public interest groups; and CBM treatment experts. EPA posted the briefing slides for the teleconferences on its project website and drafted and shared meeting minutes with participants prior to finalizing them; these minutes are available in the public docket. [2]

EPA also conducted 23 meetings outside Washington, D.C. in Alabama, West Virginia, Pennsylvania, Montana, Wyoming, Colorado, New Mexico, and Texas. Meeting participants included a broad range of stakeholders. These meetings were coordinated with site visits to CBM operations (see Section 2.2).

The meetings solicited early feedback from participants to facilitate the development of the first draft of the survey instrument and sample design. They also identified interested stakeholders for the site visits and meetings outside Washington, D.C. (see below). During these meetings, EPA provided information on the following topics:

- The EPA regulatory development process;
- An initial review of the CBM sector;
- The CBM Questionnaire; and
- The schedule and next steps.

2.2 Site Visits

EPA visited six CBM basins in eight states to gather data for the CBM Detailed Study and the questionnaire. In total, EPA visited 33 sites in different locations within these six CBM basins.

During each site visit, EPA collected general site information (e.g., location, operator name, field name, pooling arrangements, and well spacing); produced water beneficial use and disposal methods; treatment methods; and economic information such as descriptions of factors affecting decisions to begin production or shut in (cease production from) a well or lease. Information collected during each site visit is documented in a report, which is available in the public docket (EPA-HQ-OW-2006-0771 and EPA-HQ-OW-2008-0517). Confidential Business Information (CBI) in these site visit reports has been redacted from the public versions of the reports in the docket.

Table 2-1 shows the basins in which EPA conducted site visits and the number of individual visits made.

[2] See DCNs 5177–5182 and 5184 in the docket (EPA-HQ-OW-2006-0771) for meeting documentation.

Table 2-1. Site Visit Numbers and Locations

Basin	States	Number of Visits
Appalachian	Virginia, West Virginia, Pennsylvania	6
Black Warrior	Alabama	1
Green River	Wyoming	3
Powder River	Montana, Wyoming	17
Raton	Colorado, New Mexico	3
San Juan	New Mexico	3
Total Visits		**33**

2.3 Data Collection to Identify the Affected Universe

EPA licensed database information on historic well production from HPDI, Inc.[3] (a firm that compiles information from nearly all of the oil and gas producing states) to get an initial list of operator names and their associated gas production and number of wells. EPA supplemented these data with well and production data from Indiana and Illinois, states for which HPDI does not provide data. EPA also used data from West Virginia and Virginia to identify which wells in those states were CBM wells, as well as updated information from West Virginia (WVDEP) on gas production in that state.

EPA compiled the data into a database that provided information on state, basin, operator name, operator's well name and number, unique well identifier (American Petroleum Institute [API] number), field, reservoir, and various location and contact information, along with 2006 gas and water production, where available, for all operators of CBM wells in the United States (ERG, 2008). These data formed the basis for compiling the list of respondents for EPA's survey efforts, described in the sections below.

2.4 EPA CBM Industry Questionnaire

EPA collected data using two instruments: a screener questionnaire and a detailed questionnaire. The screener questionnaire focused on identifying CBM projects, which are the critical business units within the CBM industry that cannot be identified using publicly available information. A project is defined as a well, group of wells, lease, group of leases, or some other recognized unit that is operated as an economic unit when making production decisions. The detailed questionnaire focused on obtaining detailed data at the project level. EPA received approval for the Coalbed Methane Extraction Sector Survey on February 18, 2009, from the Office of Management and Budget (OMB Control No. 2040-0279).

2.4.1 Screener Questionnaire

EPA used a screener survey to ensure that it had the appropriate contact information for CBM operators that were identified in the data collection effort described in Section 0 and to provide sufficient information to stratify and select a sample of operators and projects for the detailed questionnaire. Establishments operating in more than one basin and/or state received a

[3] Use of HDPI, Inc. name should not be construed as an endorsement from EPA.

survey for each of the basins and/or states in which they operated. EPA sent the screener questionnaire in February 2009 to all CBM operators that had three or more producing CBM wells in 2006. To reduce respondent burden, EPA completed the screeners for operators identified with only one or two wells, using public data from states and from contacts with those operators in basins where surface water discharges are permitted. The screener survey database was completed in July 2009.

2.4.1.1 Description of the Screener Questionnaire

The screener survey (U.S. EPA, 2010a) requested the following information: verification that the operator produced CBM in 2008, identification of small businesses and number of projects operated, and, for each project, information on numbers of wells, gas production, and produced water management methods.

2.4.1.2 Response, Review, and Follow-up

EPA provided support to recipients in completing the screener surveys through an e-mail helpline and a toll-free telephone helpline. EPA personnel responded to e-mails and phone calls to answer questions about the instructions, standard terminology, and procedures for completing the survey, and respond to requests for guidance on the technical information requested in the survey. Additional details of how the data were updated to reflect later determinations of out-of-scope operations and the steps taken to protect CBI when reporting summary data in this report are presented in a memorandum, which is located in the administrative record (ERG, 2010).

2.4.2 Detailed Questionnaire

EPA began distributing the detailed questionnaire to the representative sample of CBM projects in late October 2009. The detailed questionnaire collects financial and technical data on more than 200 CBM projects across the country (Battelle, 2009).

2.4.2.1 Sample Selection

EPA is aware that the economics and environmental impacts of CBM production depend greatly on the location of CBM development and the surrounding ecosystem. The Agency considered location of CBM operations during the selection of projects to be surveyed. Using a sample frame of 773 projects (based on the screener survey responses), EPA selected over 200 CBM projects to receive detailed questionnaires. EPA selected the projects for sampling by basin, project size (number of wells), and discharge method (i.e., direct or indirect discharge and zero discharge). Within each sampled stratum, EPA targeted 30 percent of the projects for sampling.[4]

Generally, EPA focused on basins where screener respondents reported surface water discharges (located in the eight states noted in Table 1-1). EPA also focused on emerging zero discharge basins, which were considered likely to provide information on the types of projects that might be constructed in basins yet to be developed. These zero discharge basins included

[4] Additional details on the sampling process design are documented in an October 19, 2009, memorandum (Battelle, 2009), which is considered CBI because it reveals numbers of projects by basin and state. These totals could be used to back-calculate numbers of projects reported by respondents requesting that this information be handled as CBI.

Wind River, Arkla, Permian/Fort Worth, and Uinta-Piceance, each of which had relatively few projects, thereby requiring a census. The only stratified sampling performed was among zero discharge projects in the Wyoming portion of the Powder River Basin. EPA did not send detailed questionnaires to projects and operators in established basins that discharge no produced water directly or indirectly to surface water (Anadarko, Arkoma, and Cherokee/Forest City) because their well-developed infrastructure was not helpful for modeling conditions in newly emerging basins. The San Juan basin is a well-developed basin that received questionnaires because EPA anticipates that the San Juan basin will serve to model the emerging Black Mesa basin.

2.4.2.2 Description

The detailed questionnaire requests both technical and financial and economic data, including the following information:

- General information on the operator and parent company;
- Produced water volumes, water quality, and treatment, reuse, and disposal methods;
- Destination of CBM produced water;
- Produced water treatment methods, including system design, operating, and cost information;
- Environmental impact on receiving waters;
- Pollutant monitoring;
- Firm-level financial information; and
- Project-level financial information.

EPA used data from this survey to calculate the quality and quantity of produced waters from the CBM industry and determine means of discharge, treatment technology in place, and geographic location.

2.4.2.3 Questionnaire Response and Review and Follow-up

EPA prepared an electronic version of the detailed questionnaire to minimize operator burden and improve data quality and operated voicemail and e-mail helplines to support recipients in completing the questionnaires. Additionally, EPA began conducting follow-up activities to ensure completeness and accuracy of the questionnaire responses.

2.5 Collection and Review of Current State and Federal NPDES Regulatory Requirements

This section summarizes the current NPDES permits in key states. As noted in the executive summary, eight states allow produced water to be directly or indirectly discharged to surface water. EPA checked with six of these states to see if permits could be obtained for review and was able to review permits from four of these states'. EPA's review focused on determining common pollutants.[5]

[5] EPA did not study the permits from Illinois, Pennsylvania, Virginia, and West Virginia in detail for the following reasons. One direct discharger was identified in Illinois, but this state has very little CBM activity compared to the other states studied. Pennsylvania permits were not available for review. One indirect discharger was identified in Virginia, although it is not clear from the screener survey whether the indirect discharge was occurring in Virginia,

Initially, EPA obtained information on CBM permitting requirements via Internet searches and discussions with state permitting officials from the six major direct discharging states: Alabama, Colorado, Montana, Pennsylvania, West Virginia, and Wyoming. The Agency reviewed general and individual state NPDES permits for CBM produced water discharges in four states with information on monitoring requirements and discharge limitations. Overall, EPA determined that states use a combination of general, individual, and watershed-based permits to regulate CBM discharges to surface waters. Individual permits were issued more frequently than the other permit types, and Wyoming is the only state actively using watershed-based permits for CBM discharges.

EPA identified some common discharge and monitoring requirements across the different permitting programs. The most frequently regulated parameters include pH, chloride, TSS, Sodium Absorption Ratio (SAR),[6] oil and grease, and metals (e.g., iron and manganese). Several states require continuous monitoring of effluent flow, conductivity, and pH. Three states, Alabama, Wyoming, and Montana, include receiving stream monitoring requirements in addition to effluent monitoring. Table 2-2 lists the parameters commonly regulated in CBM produced water NPDES permits. In addition to those parameters listed in Table 2-2, Alabama, Colorado, and Wyoming also require whole effluent toxicity (WET) testing of effluent.

Table 2-2. Common NPDES Permit Parameters and Limitations

State	Number of Active Permits	Parameter	Unit	Daily Minimum	Daily Maximum	Monthly Average
Alabama	24	Chloride	mg/L	NA	230	NA
		Oil and Grease	mg/L	NA	15	NA
		pH	s.u.	6	9	NA
		Total Iron	mg/L	NA	6	3
		Total Manganese	mg/L	NA	4	2
Colorado	1 general permit covering about 20 facilities	Chloride	mg/L	NA	NA	250
		Oil and Grease	mg/L	NA	10	NA
		pH	s.u.	6.5	9	NA
		TSS	mg/L	NA	NA	30
Montana [a]	3	Oil and Grease	mg/L	NA	10	NA
		pH	s.u.	6.5	9	NA
		SAR		NA	Mar–Oct: 2.6–4.5 Nov–Feb: 6.6–7.5	Mar–Oct: 1.3–3.0 Nov–Feb: 3.3–5.0

West Virginia, or both states, and Virginia has no direct discharges to surface waters. West Virginia direct discharge permits were not yet active at the time of the study.

[6] SAR is the ratio of sodium concentrations to calcium and magnesium concentrations in water. This ratio characterizes the relative sodicity of water. That is, it measures the relative amount of Na+ ions compared with other ions in water, which is significant because sodium may affect vegetation and soil characteristics. Section 4 provides further discussion of the potential impacts from elevated SAR.

Table 2-2. Common NPDES Permit Parameters and Limitations

State	Number of Active Permits	Parameter	Unit	Daily Minimum	Daily Maximum	Monthly Average
		TSS	mg/L	NA	30–40	17–25
		Total Recoverable Cadmium	µg/L	NA	0.48	0.054
		Total Recoverable Fluoride	mg/L	NA	NA	0.5
		Total Recoverable Iron	mg/L	NA	NA	0.6
		Total Recoverable Selenium	µg/L	NA	3	0.75
Wyoming	About 800	Chloride	mg/L	NA	50–2000	NA
		Dissolved Iron	µg/L	NA	74–1000	NA
		Dissolved Manganese	mg/L	NA	50	NA
		pH	s.u.	6.5	9	NA
		SAR		NA	1–13 SAR < 7.10 × EC – 2.48	NA
		TDS	mg/L	NA	300–5000	NA

a – At the time this report was written, Montana was evaluating how to implement technology-based limits on CBM discharges.
NA – Not applicable.

Appendix A summarizes the permitting practices and requirements for each of the six states reviewed.

3. TECHNICAL AND ECONOMIC PROFILE OF THE CBM INDUSTRY

This profile covers both the technical aspects of CBM extraction and produced water production and the economic and financial characteristics of the industry. Section 3.1 describes CBM gas production and also presents the volumes of gas produced. Section 3.2 presents the volumes and quality of water produced during CBM extraction. Section 3.3 discusses the various methods for managing produced water and discusses the pollutants in produced water discharges. Section 3.4 summarizes various treatment technologies that might be used to reduce pollutants, and Section 3.5 discusses the current economics of the CBM industry, including counts of operators, numbers of wells, numbers of projects, estimates of revenues generated by those projects, and the financial conditions of publicly held firms in the industry. Section 3.6 discusses trends in key factors affecting the future economics of CBM production.

3.1 CBM Gas Production

Coalification, the geologic process that progressively converts plant material to coal, generates large quantities of natural gas, which are subsequently stored in the coal seams. The increased pressures from water in the coal seams force the natural gas to adsorb to the coal. The natural gas consists of approximately 96 percent methane, 3.5 percent nitrogen, and trace amounts of carbon dioxide (U.S. EPA, 2004a). This natural gas contained in and removed from the coal seams is called coalbed methane or CBM. (U.S. DOE, 2006)

The amount of available methane in coal varies with coal's hardness (the resistance to scratching). Level of hardness is known as "rank." The softest coals (peats and lignites) are associated with high porosity, high water content, and biogenic methane. In higher-rank coals (bituminous), porosity, water, and biogenic methane production decreases, but the heat associated with the higher-rank coals breaks down the more complex organics to produce methane. The highest-rank anthracite coals are associated with low porosity, low water content, and little methane generation (ALL, 2003). The most sought-after coal formations for CBM development, therefore, tend to be mid-rank bituminous coals. Coal formations in the eastern United States tend to be higher-rank, with lower water content than western coal formations. They also tend to have more methane per ton of coal than western coal formations in the key basins, but can require fracturing to release the methane because of their low porosity (ALL, 2003).

Extraction of CBM requires drilling and pumping the water from the coal seam, which reduces the pressure and allows CBM to release from the coal (Wheaton et al., 2006; U.S. DOE, 2006). CBM extraction often produces large amounts of water, as shown in Section 3.2. Methane and water are piped from individual wells to a metering facility, where the amount of production is recorded. The methane then flows to a compressor station, where the gas is compressed and then shipped via pipeline (De Bruin, et al., 2001). The produced water is a by-product of the gas extraction process, requiring some form of management (i.e., use or disposal).

Well construction for any well drilling operation—including a CBM well—usually follows one of two basic types: open hole or cased. In open-hole completions, the well is drilled but no lining material is installed, so any gas can seep out all along the well into the wellbore for removal to the surface. In cased completions, a lining is installed through all or most of the wellbore. These casings need to be perforated or slotted to allow gas to enter the wellbore for removal to the surface. Open-hole completions, which are less expensive than perforated or slotted completions, are used more often in CBM production than in conventional oil and gas production, which use open-hole completion only under certain limited circumstances (NaturalGas.org, 2004). For example, open-hole completion is widely used in Wyoming's Powder River Basin (PRB) (ALL, 2003). Figure 3-1 shows the profile of a typical western CBM well using open-hole completion.

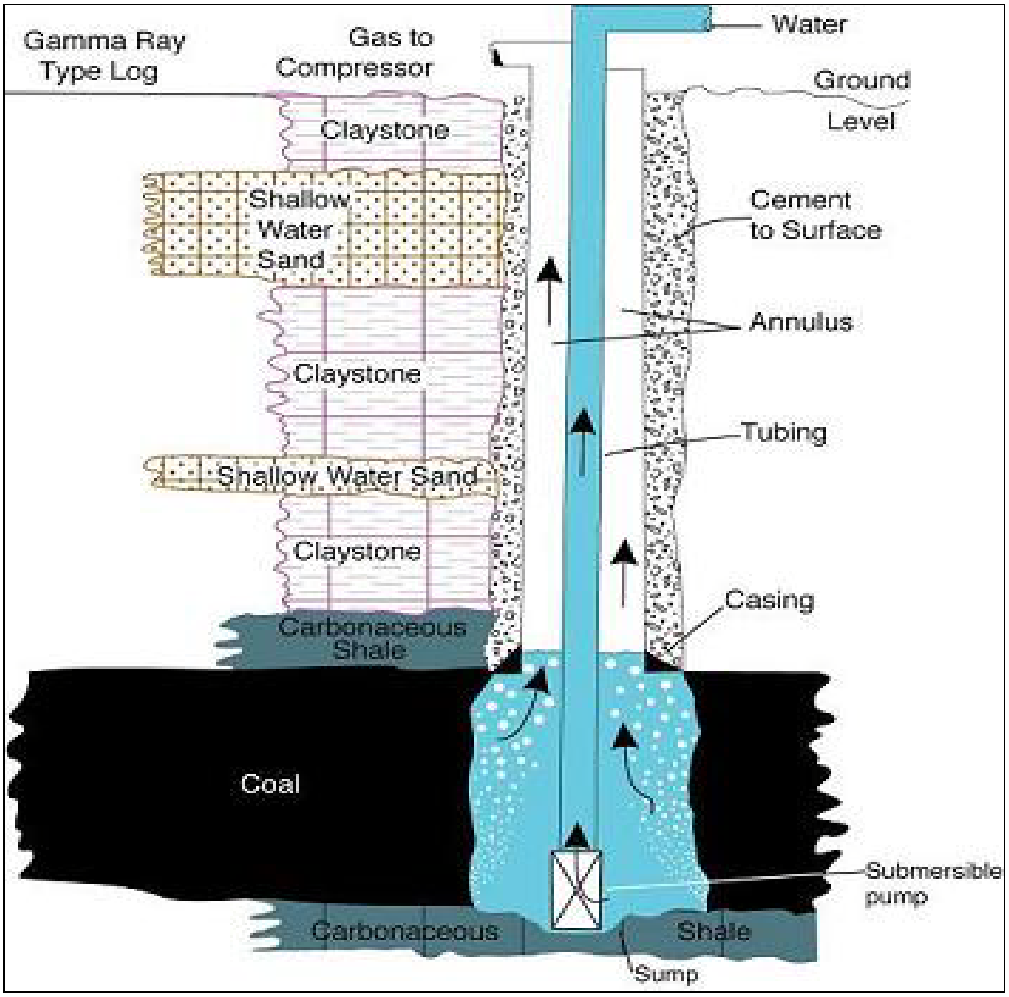


Figure 3-1. Profile of a Typical Western CBM Well With Open Hole Completion (DeBruin, et al., 2001)

Operators drill wells into coal-bearing formations that are often not as deep as those containing conventional hydrocarbon reserves, particularly in western regions. In the PRB, for example, some of the methane-bearing formations are shallow, at hundreds to one thousand feet below land surface, compared to conventional oil and natural gas well depths averaging approximately 6,000 feet (U.S. DOE, 2005). CBM wells can often be drilled using water well drilling equipment, rather than rigs designed for conventional hydrocarbon extraction, which are used to drill several thousands of feet into typical conventional reservoirs (Apache Corporation, 2006).

A CBM well's typical lifespan is between 5 and 15 years, with maximum methane production often achieved after one to six months of water removal (Horsley & Witten, 2001). CBM wells go through the following production stages:

- An early stage, in which large volumes of groundwater are pumped from the seam to reduce the underground pressure and encourage the natural gas to release from the coal seam;
- A stable stage, in which the amount of natural gas produced from the well increases as the amount of groundwater pumped from the coal seam decreases; and
- A late stage, in which the amount of gas produced declines and the amount of groundwater pumped from the coal seam remains low (De Bruin, et al., 2001).

3.1.1 History of Production in the CBM Basins

Table 3-1 shows the major CBM production basins (including those where no development has taken place), their locations, typical well depths, and the thickness and depth of CBM seams. Interest in producing methane gas from coal seams began in the 1970s, but little development occurred until the early 1980s. In 1983 the Gas Research Institute began a field study investigating the potential for producing methane gas from coalbed strata (Fisher, 2001). By the end of that year, 165 wells had been drilled, producing about 6 billion cubic feet (Bcf) of gas, less than 1 percent of the amount produced in 2008. The first area to be developed was the Black Warrior Basin in Alabama, followed by the San Juan Basin in New Mexico and Colorado, which began development in the latter part of the 1980s. For many years, CBM was almost exclusively produced from these three states (Fisher, 2001). Production in the PRB began in earnest in the early 1990s, and the PRB quickly became a major source of CBM by the end of the 1990s (Wyoming Oil and Gas Conservation Commission [WOGCC], 2010). Although not increasing as rapidly since that time, production has risen fairly steadily. By 2000, Wyoming was producing 10 percent of all CBM; by 2008, production in the state was approaching a third (U.S. DOE EIA, 2010a; U.S. EPA, 2010a).

The older basins, such as San Juan and Black Warrior, have not seen growth in CBM production during the 2000s. San Juan production appears to have peaked in 2002, with some decline since then. Black Warrior production has been level in the 2000s (U.S. DOE EIA, 2010a). The rise in U.S. production over time has been driven primarily by production in Wyoming, mostly in the PRB. Production in several other basins has also increased over time, although these basins contribute less to CBM production growth than PRB (U.S. DOE EIA, 2010a). Several additional basins are of interest for future CBM production, although little to no development is currently underway. Section 3.6.4 discusses the future of CBM production in the various basins.

Table 3-1. Characteristics of Major CBM Basins

Basin	Location/Area	Coalbed Thickness	Well Depth or Depth to Target Coal Seam
Appalachian (Central)	23,000 square miles in Kentucky, Tennessee, Virginia, and West Virginia with greatest potential for development in a 3,000 square mile area in southwest Virginia and south central West Virginia	Variable	1,000 to 2,000 feet
Appalachian (Northern)	43,700 square miles in Kentucky, Maryland, Ohio, Pennsylvania, Virginia, and West Virginia	Average of 25 feet in Pennsylvania	Ranges from surface outcrops to depths of 2,000 feet with most occurring at depths of less than 1,000 feet
Arkoma	13,500 square miles in Arkansas and Oklahoma	600 to 2,300 feet	0 to 4,500 feet
Black Warrior	• Covers about 23,000 square miles in Alabama and Mississippi • Measures approximately 230 miles east-west and 188 miles north-south	1 to 8 feet	350 to 2,500 feet
Cherokee/Forest City	• Cherokee is 26,500 square miles in Oklahoma, Kansas, and Missouri • Forest City is 47,000 square miles in Iowa, Kansas, Missouri, and Nebraska	Few inches to 6 feet	Depth to coal in the shallow portion of Cherokee ranges from surface to 230 feet and up to 1,200 feet in the deeper portion
Greater Green River	Comprises five smaller basins in Wyoming, Colorado, and Utah	Multiple coal seams up to 50 feet thick	Not Readily Available
Illinois	Northwestern Kentucky, southeastern Indiana, and Illinois	Multiple thin coal seams	Most seams are at less than 650 feet; across the basin, all seams are less than 3,000 feet deep
Piceance	7,225 square miles in Northwest Colorado	2,000 feet on west side to 6,500 feet on east site	Depth to methane-bearing formation is 6,000 feet, which has hindered development
Powder River Basin	25,800 square miles in northeastern Wyoming and southern Montana	Ranges by formation – Wasatch Formation has thin coals (6 feet or less) while Fort Union coals, which are below Wasatch, can be up to 6,200 feet thick	450 to 6,500 feet

Table 3-1. Characteristics of Major CBM Basins

Basin	Location/Area	Coalbed Thickness	Well Depth or Depth to Target Coal Seam
Raton	• 2,200 square miles in southeastern Colorado and northeastern New Mexico • Measures 80 miles north-south and as much as 50 miles east-west	Vermejo coals are 5 to 35 feet thick and Raton coal layers are 10 to 140 feet thick	Not Readily Available
San Juan	• Covers an area of about 7,500 square miles across the Colorado/New Mexico line in the Four Corners region. • Measures approximately 100 miles north-south direction and 90 miles east-west.	Majority of production is in the Fruitland Formation. Coals of the Fruitland Formation range from 20 to over 40 feet thick	Wells drilled into the Fruitland coal seam typically range from 600 feet to 3,500 feet
Uinta	Eastern Utah (small portion in northwestern Colorado) covering 14,450 square miles	Exploration in Ferron Coals and Blackhawk formation	Depths to coal range from 1,000 to 7,000 feet
Wind River	Central Wyoming east of Powder River Basin	Potential for development in Upper Cretaceous Formation with thicknesses of up to 100 feet and Meeteetse Formation with thicknesses of less than 20 feet	Not Readily Available

Sources: U.S. EPA, 2004a, U.S. EPA, 2004b; ARI, 2010b; ALL, 2003.

3.1.2 CBM Production

CBM production in 2008 totaled nearly 2 trillion cubic feet (Tcf) of gas (U.S. EPA, 2010a),[7] when compared to a total of 25.8 Tcf of all forms of natural gas was produced (U.S. DOE EIA, 2010b); CBM composed about 8 percent of all natural gas produced, and is considered an important ongoing supply of energy by U.S. DOE.

In 2008, according to EPA's screener survey database,[8] 252 operators managed approximately 56,000 CBM wells in the United States in 15 basins located in 16 states (U.S. EPA, 2010a). Table 3-2 identifies all of the currently (as of 2008) producing basins and presents CBM production by basin.[9] More than two-thirds of all CBM produced in 2008 was produced in the San Juan and Powder River Basins (69 percent). About 88 percent was produced by the five largest producing basins (San Juan, Powder River, Appalachian, Raton, and Black Warrior). In the Powder River, Green River, Raton, Black Warrior, Cahaba, Appalachian, and Illinois basins, some produced water is discharged to surface waters or POTWs. In the remaining basins the only practice is zero discharge. In 2008, roughly 50 percent of total CBM was produced in basins in which some surface water discharge is occurring.

By far the largest producing states are Wyoming and New Mexico. Wyoming contains the largest portions of the PRB and Green River as well as the Wind River Basin. New Mexico contains most of the San Juan Basin and a portion of the Raton Basin.

Table 3-2. CBM Production by Basin in 2008

Basin	State(s)	CBM Production	
		Total (Bcf)	Percentage of Total
PRB	WY, MT	607	31%
Green River	WY, CO	13	1%
Raton	CO, NM	129	6%
Black Warrior	AL	104	5%
Cahaba	AL	4	0%
Appalachian and IL	PA, WV, VA, OH, IN, IL	144	7%
San Juan	NM, CO	755	38%
Cherokee/Forest City	KS	79	4%

[7] There are some discrepancies in the screener database from published figures for some basins. Both the screener and detailed survey ask for production; for the screener survey, operators might have approximated their production; whereas operators might have provided more exact production figures from the project financial records needed to complete the detailed survey. Alternatively, some states' production data might be less accurate than the operators' records; additionally, some wells are classified in some states as confidential wells. It is not certain that published data contain information on confidential wells. Most state websites indicate that they do not warrant the accuracy of their data.

[8] For information in the screener to be reported without concern that CBI would be revealed, the screener database was modified to replace CBI data with publicly available data on numbers of wells and gas production. Additionally, projects identified as out of scope later during implementation of the detailed questionnaire were also removed from the screener database. The modifications made to the screener database are documented in (ERG, 2010).

[9] The Appalachian Basin and Illinois Basin have been combined here, in part, to maintain confidentiality of CBI as noted in ERG, 2010.

Table 3-2. CBM Production by Basin in 2008

Basin	State(s)	CBM Production	
		Total (Bcf)	Percentage of Total
Uinta-Piceance	CO, UT	65	3%
Arkoma	OK, AR	66	3%
Anadarko	OK, AR	18	1%
Other	LA, TX, WY	3	0%
Total		**1,988**	**100%**

Source: U.S. EPA, 2010a.

3.1.3 Potential for Development in New CBM Basins

The basins that have been developed to date are those with mid-rank coals (coals with more energy associated with them and generally more gas than lowest-rank and highest-rank coals). Additional CBM prospects exist in other areas in the United States that have not yet been developed. Table 3-3 summarizes prospective but nonproducing CBM resources. Because of the existing pipeline infrastructure, coal rank, and coal volume, the most likely basin to produce commercial quantities of CBM over the next 10 years is the Black Mesa Basin (ARI, 2010a).

Table 3-3. Prospective But Nonproducing CBM Resources

Region Name	Location	Estimated Gas in Place (Tcf)	Status
Alaska—Cook Inlet	Southern Alaska	136	Located close to existing Kenai LNG facility. One unsuccessful pilot plant that was built can provide data for further development.
Alaska—North Slope	Far northern Alaska	621	No development to date because of remoteness from markets; not characterized; pipeline planned to transport natural gas to southern markets could benefit CBM.
Pacific Northwest Coal Region	Washington and Oregon	10	Geologically complex area makes gas recovery challenging. No conventional gas production in the region is a positive market factor. Some testing demonstrated good gas content, permeability, and gas flow rates.
Black Mesa Basin	Northeastern Arizona	1–10	Large-scale surface mining in the area since the 1960s but no CBM testing to date. Could access market via recently constructed Questar Southern Trails gas pipeline.
Low-Rank Coals in the Gulf Coast	Florida panhandle to Texas Gulf Coast	1.7–7.9	Gas-rich coals occur below 3,000 feet. Over 400,000 acres have been leased and individual test pilots have been installed. Exploration is active in north central Louisiana following 2005 revision of state law to accommodate CBM. Exploration is also active in Maverick County in southcentral Texas.

Table 3-3. Prospective But Nonproducing CBM Resources

Region Name	Location	Estimated Gas in Place (Tcf)	Status
Other Low-Rank Coals	North Dakota, Northern Montana, Michigan	Unknown	Little work done to date to assess the CBM potential of lignite coals, but anecdotal evidence from water well drillers suggests CBM exists in North Dakota lignite.

Source: ARI, 2010a.

3.2 Produced Water Characteristics

EPA evaluated the quality and quantity of produced water generated from CBM extraction using preliminary data from responses to the detailed survey questionnaires and other sources. As discussed in Section 3.1, water within the coal seam usually must be removed before and during CBM production. The quantity and quality of this produced water varies from basin to basin, and even within the basin itself. The quality of produced water depends, in part, on the hardness of the coal found within the formation. The quantity of produced water depends on type of coal and the overall production history of the basin. Basins with a longer production history, such as the San Juan basin, produce less total water and less water per well than the more recently developed basins, such as the PRB.

3.2.1 Volumes of Produced Water

Based on preliminary data from the detailed questionnaire responses, EPA estimated that, in 2008, more than 47 billion gallons of produced water were pumped out of coal seams and approximately 22 billion gallons of that produced water (or about 45 percent) were discharged to surface waters. Table 3-4 presents preliminary volumes of produced water discharged (basins not listed here do not discharge).

Table 3-4. Volumes of CBM Produced Water Discharged to Surface Waters in the Discharging Basins (2008)

Basin	Volume (million gallons/year) [a]
Appalachian	32.3
Black Warrior	2,454.3
Cahaba	244.0
Green River	327.1
Illinois	113.4
Powder River (Montana)	1,266.8
Powder River (Wyoming)	14,622.5
Raton	2,515.8
Total	**21,543.9**

Source: Preliminary detailed questionnaire data (U.S. EPA, 2010b).
a – The volume totals for each basin do not include discharges to POTWs, which are minimal.

3.2.2 Pollutants in Produced Water

CBM produced water is generally characterized by elevated levels of salinity, sodicity, and trace elements (e.g., barium and iron) (ALL, 2003). Other trace pollutants that may be present in produced water include potassium, sulfate, bicarbonate, fluoride, ammonia, arsenic, and radionuclides. The characteristics of the produced water depend on the geography and location (e.g., naturally occurring elements). All of these parameters can cause adverse environmental impacts (see Chapter 4) and also affect the potential for beneficial use of produced water.

Salinity represents the total concentration of dissolved salts in the produced water, including magnesium, calcium, sodium, and chloride. Salinity can be measured as electrical conductivity (EC), expressed in deciSiemens per meter (dS/m), as well as total dissolved solids (TDS). TDS includes any dissolved minerals, salts, metals, cations, or anions in the water. The salinity of CBM produced water also relates to the measured sodicity value.

Sodicity is excess sodium present in produced water that can deteriorate soil structure (i.e., swell and disperse clays reducing pore size), which reduces the infiltration of produced water through the soil. The sodicity of produced water is expressed as the SAR, which is the ratio of sodium (Na) present in the water to the concentration of calcium (Ca) and magnesium (Mg) (Equation 3-1).

$$SAR = \frac{[Na^{+}]}{\sqrt{\frac{1}{2}\left([Ca^{2+}] + [Mg^{2+}]\right)}} \qquad \text{Equation 3-1}$$

Table 3-5 presents available literature data for minimum and maximum produced water TDS concentrations in 9 of the 15 CBM basins (data were obtained separately for each portion of the Uinta-Piceance Basin). EPA used these data to estimate average TDS concentrations in each of the basins where such data were available. When this average might not accurately reflect the TDS concentrations in produced water basin-wide, EPA substituted other values were used that were deemed to be more representative. As the table shows, EPA estimates that average TDS concentrations vary widely, from approximately 1,100 mg/L TDS in the Powder River Basin up to 86,000 mg/L in the San Juan Basin. For comparison, the recommended TDS limit for potable (drinking) water is 500 milligrams per liter (mg/L) and 1,000 to 2,000 mg/L (USGS, 2000) for irrigation and stock ponds.

EPA used preliminary questionnaire discharged flow volumes from Table 3-4 and the concentration estimates presented in Table 3-5 to calculate approximate TDS discharges from CBM operations. EPA estimated that approximately 500 million pounds of TDS from CBM production operations were discharged to surface waters in 2008.[10]

[10] To compute the total TDS discharge, EPA used concentrations from the Black Warrior Basin to estimate the concentrations for the Cahaba and Illinois basins (data from ALL, 2003).

Table 3-5. TDS Concentrations in CBM Produced Water by Basin

Basin	Minimum (mg/L)	Maximum (mg/L)	Average (mg/L)	Average (lbs/gal)
Appalachian	<10,000	>10,000	10,000	0.0835
Black Warrior	<50	60,000	16,000	0.1335
Cahaba	<50	60,000	16,000	0.1335
Green River	ND	>10,000	5,000	0.0417
Illinois	<50	60,000	16,000	0.1335
Powder River	244	8,000	1,066	0.0089
Raton	310	>3,500	1,905	0.0159
San Juan	180	171,000	85,590	0.7143
Uinta	6,350	42,700	24,525	0.2047
Piceance	1,000	6,000	3,500	0.0292

Source: U.S. EPA 2006, U.S. EPA 2010b.
ND – Not detected.

The available literature also yielded concentration data for other pollutants for five of the basins (see Table 3-6).

Table 3-6. Pollutant Concentrations in CBM Produced Water by Basin

Pollutant	Pollutant Concentration by Basin (mg/L)									
	San Juan Basin		Black Warrior Basin		Powder River Basin		Raton Basin		Uinta Basin	
	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max
Barium	0.7	63	NA	NA	0.06	2	NA	NA	NA	NA
Calcium	0	228	NA	NA	5	200	4	24	NA	NA
Chloride	0	2,350	40	36,000	3	119	15	719	2,300	14,000
Iron	0	228	0.1	400	0.03	11	0.1	23	NA	NA
Magnesium	0	90	NA	NA	1	52	1	8	NA	NA
Potassium	0.6	770	NA	NA	2	20	1	17	NA	NA
Sodium	19	7,130	60	21,500	89	800	210	991	NA	NA
Sulfate	0	2,300	1	1,350	0.01	1,170	1	204	NA	NA

Source: U.S. EPA 2006.
Min – Minimum.
Max – Maximum.
NA – No data available.

3.3 Management of Produced Water

CBM well operators use a variety of methods to manage, store, treat, and dispose of CBM produced water. Figure 3-2 shows the potential path of produced water. As mentioned in Section 2.4, CBM is usually produced from a project, which is defined as a well, group of wells, lease, group of leases, or some other recognized unit that is operated as an economic unit when making production decisions. The produced water from the project might be managed using various storage, treatment, and disposal methods, and each CBM project can use several different management methods.

All CBM operators need a system gathering and transporting produced water. CBM produced water from individual wells is often gathered via a pipeline system to transport the water to a centralized storage system and then to either a treatment system or the final disposal location. Section 3.4 discusses common treatment methods. The final destination of CBM produced water may include the following:

- Discharge – Either direct discharge to surface water or indirect discharge to a POTW (Section 3.3.1);
- Zero discharge (with no beneficial use) – Zero discharge might include evaporation/infiltration,[11] underground injection, or land application with no crop production (Section 3.3.2); and
- Zero discharge (with beneficial use) – Beneficial use might include land application, wildlife watering, or other miscellaneous beneficial uses (Section 3.3.3).

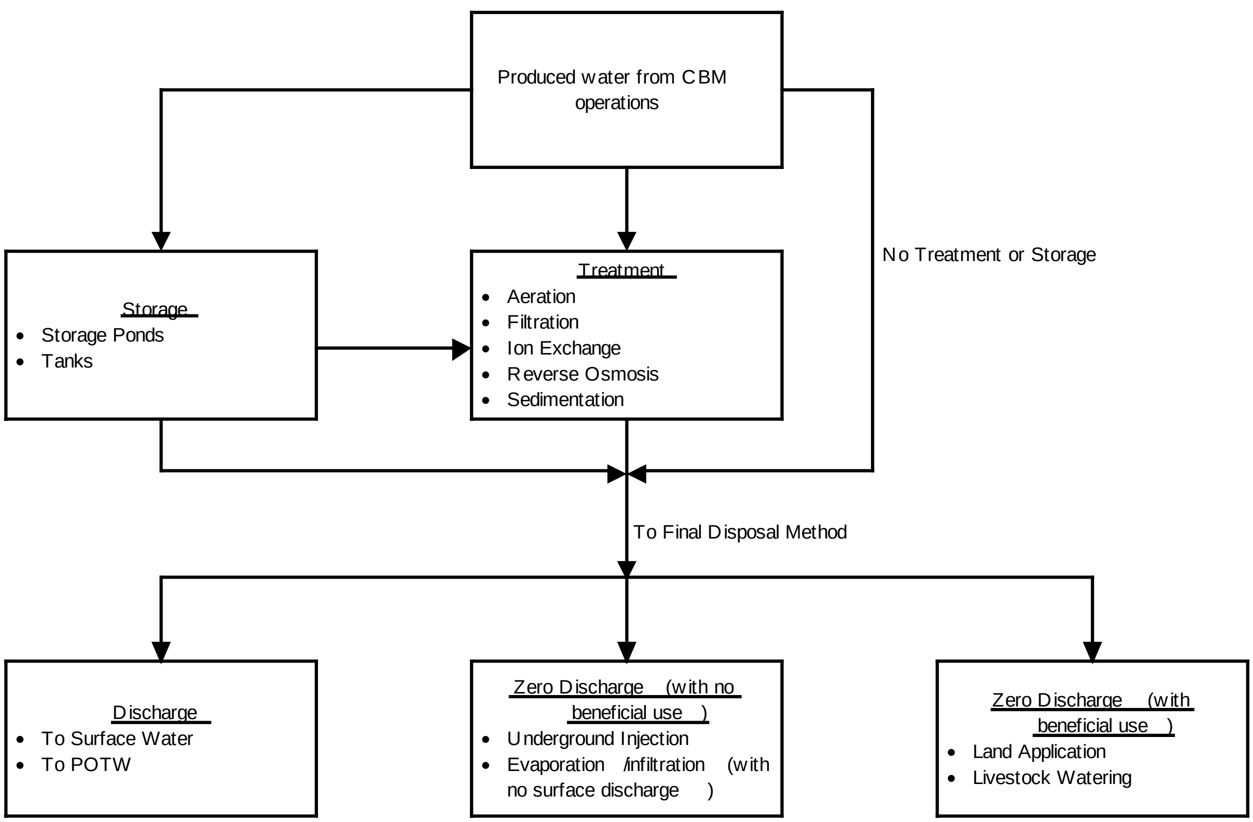


Figure 3-2. Diagram of Potential Path of Produced Water

Operators may contract with a commercial disposal company to manage the wastewater. Typically, the produced water is stored on site in tanks and later hauled to the third-party

[11] CBM operators may also use evaporation/infiltration to reduce the amount of produced water discharged to surface water.

company. Sections 3.3.1 through 3.3.3 and Section 3.4 discuss the disposal and treatment methods in more detail.

The produced water management methods used in a particular basin depend on a variety of factors such as water quantity, water quality, availability of receiving waters, availability of formations for injection, landowner interests, and state regulations. Table 3-7 lists each basin included in EPA's site visit program, the typical management and disposal practices in use, the factors affecting the management practice, and treatment and beneficial use methods observed during the site visit program.

The screener survey provided EPA with information on which produced water management practices are used at each project. These management practices are divided into two major groups: discharging practice (direct discharge to surface waters or indirect discharge to a POTW) or zero discharge practice (land application, evaporation/infiltration pond, underground injection, beneficial use, transport to a commercial disposal facility, or no water generated).

The basins in which direct or indirect discharge is practiced are called "discharging basins" in this profile and include the Powder River, Appalachian, Illinois, Raton, Black Warrior, Cahaba, and Green River Basins. EPA determined that, in other basins, CBM operators manage produced water without discharging any portion of it directly or indirectly to surface waters. In these basins, called "zero discharge basins" in this profile, produced water is managed primarily by underground injection, trucking to a commercial disposal facility, or collection in ponds for use by livestock/wildlife (beneficial use) or in evaporation/percolation ponds.

Table 3-8 presents the number of projects using the various produced water management methods by basin. Note that the numbers reported reflect multiple produced water management practices at many projects. For example, a project might be reported to use surface water discharge, evaporation/infiltration ponds, and underground injection. For the purposes of this profile, such a project is considered a discharging project because at least some produced water is reported to be discharged to surface waters. Only projects reporting no direct or indirect discharge are considered zero discharge projects.[12]

[12] Nine CBI "projects" use some type of zero discharge practice; these projects are not reflected in the counts presented in Table 3-8 to protect potential confidential information. EPA set projects per operator per basin to one for all operators claiming project information as CBI (see ERG, 2010).

Table 3-7. CBM Produced Water Management Practices Observed During Site Visits

Basin	Management and Disposal Practices in Use	Factors Affecting Management Option	Treatment Technologies Observed During Site Visit	Beneficial Use Observed During Site Visit
Appalachian (Central)	• Injection • Land application (with no crop production) • Surface discharge	• Availability of large receiving water bodies • Land application is permitted under West Virginia general permit	• Sedimentation	None observed
Appalachian (Northern)	• Injection • Surface discharge	• Availability of large receiving water bodies	• Aeration • Sedimentation (Pennsylvania does not allow the use of chemical coagulants to treat CBM produced water)	None observed
Black Warrior Basin	• Surface discharge	• Availability of large receiving water bodies • Geological formations can not handle the volumes of produced water	• Operators typically use a combination of storage ponds, sedimentation, and aeration	None observed
PRB	• Injection • Surface discharge • Evaporation/infiltration ponds	• High volumes of water with low salinity	• Aeration • Sedimentation • Ion exchange	• Land application • Livestock watering • Subsurface drip irrigation (SDI) • Small amounts may be used for dust suppression
Raton	• Injection • Surface discharge		• Aerated storage ponds	• Small amounts may be used for dust suppression • Livestock watering
San Juan	• Injection • One operator is an indirect discharger	• Availability of formations for injection • High salinity of produced water • State regulations	• Altela thermal distillation system is used for the indirect discharger	None observed

Source: DCN 05354.

Table 3-8. Number of Projects by Produced Water Management Practices Reported

Basin	Direct Discharge	Indirect Discharge	Land Application	Underground Injection	Evaporation/ Infiltration Pond	Beneficial Use [a]	Haul to Commercial Disposal	No Water Generated
Discharging Basins								
Powder River	149	2	29	31	145	154	4	4
Green River	3	0	0	10	1	1	2	0
Raton	3	0	0	3	3	1	2	0
Black Warrior	13	0	0	0	1	0	2	0
Cahaba	2	0	0	1	0	0	1	0
Appalachian and Ill.	8	3	2	15	7	0	7	1
Total, Discharging Basins	178	5	31	60	157	156	18	5
% of Projects Reporting	29%	1%	5%	10%	26%	26%	3%	1%
Zero Discharge Basins								
San Juan	0	0	0	58	2	1	142	2
Cherokee/Forest City	0	0	0	25	0	0	3	0
Uinta-Piceance	0	0	0	11	2	0	2	0
Arkoma	0	0	0	16	0	0	153	2
Anadarko	0	0	0	14	0	0	6	1
Other	0	0	0	2	0	0	1	0
Total, Zero Discharge Basins	0	0	0	126	4	1	307	5
% of Projects Reporting	0%	0%	0%	28%	1%	0%	69%	1%

Source: U.S. EPA, 2010a. Note: Zero discharge practices claimed as CBI are not reported here (see ERG, 2010); counts reflect multiple practices at many projects.
a – Livestock and wildlife watering.

As Table 3-8 shows, in zero discharge basins, the primary produced water management practices are underground injection and hauling for commercial disposal. In discharging basins, in addition to direct and indirect surface water discharge, operators also use zero discharge methods. In these basins, evaporation/infiltration ponds and beneficial use (livestock and wildlife watering) are common zero discharge practices; underground injection and hauling are less common. Land application, another practice that can be considered zero discharge, is relatively rare and found primarily in the PRB and, as witnessed during site visits, in the Appalachian basin. Land application under proper circumstances (e.g.., with produced water with low SAR and other pollutants) can be considered beneficial use (e.g., irrigation). Only 10 projects, located primarily the Powder River, San Juan, and Arkoma Basins, produced no water in 2008.

3.3.1 Discharge to Surface Water or POTW

Based on screener survey responses, EPA determined that CBM well operators in a number of basins discharge at least a portion of their produced water directly to surface water. Screener responses indicated that indirect discharge of produced water is not common; only three operators with five projects (two in the PRB and three in the Appalachian Basin) discharged produced water to a POTW in 2008; during site visits, EPA also observed indirect discharges in basins other than PRB and the Appalachian as listed in Table 3-14. Discharge to surface water is most prevalent (by volume) in the Black Warrior, Powder River, and Raton Basins. Using preliminary questionnaire data, EPA estimated that approximately 22 billion gallons of produced water are discharged annually to surface waters. CBM well operators typically transport produced water to the discharge location via buried pipelines (i.e., gathering system).

3.3.2 Zero Discharge (with No Beneficial Use)

The following subsections describe zero discharge disposal methods that are not considered beneficial use.

3.3.2.1 Evaporation/Infiltration Impoundments

Operators use earthen storage impoundments (ponds) to manage the produced water by allowing the water to evaporate or penetrate into the soil and become groundwater. Impoundments may also be used for storage or in conjunction with surface water discharge to control the wastewater flow to the outfall.

The impoundments are typically excavated rectangular pits with sloped sides and perimeter berms. There are two types of impoundments used for evaporating or infiltrating produced water: in-channel and off-channel. In-channel ponds are located within an existing drainage basin, including all perennial, intermittent, and ephemeral defined drainages, lakes, reservoirs, and wetlands. Off-channel ponds are located in upland areas, outside natural drainages and alluvial deposits associated with these natural drainages (Pochop et al.,1985).

Many CBM well operators in the PRB manage produced water in impoundments to minimize or eliminate the amount of wastewater discharging to surface water. Most of the impoundments in the PRB are off-channel and are designed to contain all CBM produced water without discharge (Oil & Gas Consulting, 2002).

3.3.2.2 Underground Injection

The Underground Injection Control (UIC) Program, under the Safe Drinking Water Act, ensures that injection wells do not endanger current and future underground sources of drinking water (USDW). USDW are defined as aquifers or portions of aquifers that contain less than 10,000 mg/L of TDS and have enough groundwater to supply a public water system. Currently there are five classes for deep wells used for disposal. EPA defines these classes (listed in Table 3-9) according to the type of fluid and location (U.S. EPA, 2005).

Table 3-9. UIC Program: Well Classes and Description

Well Type	Injection Well Description
Class I	Wells used to inject fluids underneath the lowermost formation containing USDW
Class II	Wells used to inject nonhazardous fluids associated with oil and natural gas recovery and storage of liquid hydrocarbons
Class III	Wells associated with solution mining (e.g., extraction of uranium, copper, and salts)
Class IV	Wells used to inject hazardous or radioactive waste into or above USDW
Class V	Any injection well that is not contained in Classes I to IV

Source: U.S. EPA, 2005.

The type of injection well CBM operators can use to manage produced water are Class II. By injecting produced water with high salt content or other contaminants deep underground, Class II wells prevent surface contamination of soil and water. CBM produced water typically has lower TDS concentrations than the water in the injection zone. If the well is properly designed, maintained, and operated, there is little risk of groundwater contamination from produced water. However, this practice can be limited by the availability of suitable formations to accept the volumes of water injected (e.g., high-porosity formations located below saline aquifers to avoid any potential for drinking water contamination). Under federal and state requirements, the produced water must be injected into the originating formation or into formations that are similar to those from which it was extracted (Zimpfer et al., 1988).

Operators install Class II wells by either drilling new holes or converting existing wells such as marginal oil-producing wells, plugged and abandoned wells, and wells that were never completed (dry holes). Some operational difficulties associated with injecting CBM produced water include formation plugging and scaling, formation swelling, corrosion, and incompatibility of injected produced water with receiving formation fluids. In general, these issues can be avoided or remedied by using engineering and operational applications such as treatment chemicals (U.S. EPA, 1996).

Pretreatment for injection may include removing iron and manganese by precipitation. Iron and manganese form oxides upon exposure to air, which may clog the well. Settling tanks with splash plates aerate the produced water, which oxidize iron and manganese to insoluble forms that can precipitate in the tank. Biocides may also be added to the produced water prior to injection to control biological fouling.

3.3.2.3 Land Application (with No Crop Production)

EPA observed the disposal of produced water by land application with no crop production in West Virginia (Appalachian Basin). In West Virginia, produced water may be disposed of by land application based on the quality of the water and the land's ability to assimilate the water. The produced water is land applied such that there is no runoff to surface water. In West Virginia, water quality parameters that limit land application of CBM water are chloride content and TDS. Land application may not be feasible for reasons including wet or frozen conditions or soils with high clay fractions that may impede produced water from infiltrating into the soil, causing it to run off into nearby streams or rivers. Any conditions causing limited infiltration preclude land application, and other disposal methods must be used.

3.3.3 Zero Discharge (with Beneficial Use)

The beneficial use of CBM produced water is defined as a use that provides a service to local communities and ecosystems without resulting in the direct discharge of produced water to surface waters. Beneficial uses include irrigation of cropland and pastureland without return flows to drainages and livestock and wildlife watering (Oil & Gas Consulting, 2002).

Water quality and quantity are the primary characteristics of CBM produced water that determine the potential beneficial use options at a CBM site. For example, concentrations of certain trace elements such as arsenic, manganese, and zinc can limit the beneficial use options available due to the elements' potential toxicity to humans and the environment. In addition, other site-specific constraints such as water rights, permitting regulations, location, and cost may limit the beneficial use management options available at a given site.

3.3.3.1 Land Application (with Crop Production)

The quality of CBM produced water and the physical and chemical properties of the irrigated soils determine whether produced water can be used for irrigation. The three primary water quality considerations of produced water for irrigation applications are salinity, sodicity, and toxicity (see Section 4.3.1). When CBM produced water is used for irrigation, soil samples are periodically analyzed to ensure that the application will not cause plugging or dispersal (and subsequent erosion) of the soil structure. Soil sample analytes include SAR, EC, pH, and soil moisture (to confirm that water is being absorbed). Complete soil chemistry and hydraulic properties are also analyzed and reviewed on a periodic basis. Soil amendments (e.g., gypsum) may be added to improve the physical properties of the soil.

EPA observed subsurface drip irrigation (SDI) systems developed by BeneTerra, LLC, to beneficially use CBM produced water. BeneTerra currently operates SDI systems in the Powder River Basin. In Wyoming, SDI systems are permitted under the Wyoming Department of Environmental Quality's (WYDEQ) UIC program as Class V injection disposal wells.

BeneTerra's SDI system disperses produced water through polyethylene tubing placed below ground level. BeneTerra contracts with energy companies to design, build, and operate the SDI systems for a given period of time. Surface and water use agreements are made among all parties – the CBM operator, landowner, and BeneTerra. BeneTerra agrees to disperse a set volume of water over a set contract period, works with the landowner to determine the type of crops that will be grown on the irrigated area, and determines the soil amendments required to maintain the proper soil chemistry given the type of crop and the produced water quality. BeneTerra also uses groundwater modeling to predict the subsurface flow of the injected CBM produced water to ensure that it does not connect with surface waters (U.S. EPA, 2007).

3.3.3.2 Livestock and Wildlife Watering

CBM produced water used for livestock watering is typically stored either in system reservoirs and stream drainages or in small containment vessels (e.g., tire tanks). Spacing stored water throughout grazing lands or letting it overflow to a drainage system allows landowners to distribute water to their livestock in selected locations on ranch lands, which can prevent or reduce livestock impacts to naturally occurring surface waters.

Similar to livestock watering, CBM produced water can be stored in ponds to provide additional water sources to support drinking water needs and habitat requirements for local wildlife. In general, wildlife watering ponds improve the diversity of habitats available, increase wildlife populations and ranges in the region, and enhance community dynamics in the local ecosystem (ALL, 2003). In some cases, wildlife watering ponds may also improve the quality of water available to wildlife and provide habitats for transient populations such as migrating birds during the winter season.

3.3.3.3 Industrial Uses

Another possible beneficial application of CBM produced water is industrial operations, such as energy extraction industries, cooling towers, or fire protection. As with all disposal methods, using produced water in industrial applications depends on the quality of the produced water and the water quality required for the application. During the site visit program, EPA observed CBM operations that use produced water for dust suppression during drilling or mining activities and for equipment washing.

3.4 Treatment Methods

Operators may treat the CBM produced water prior to discharge or other management. The level of CBM produced water treatment depends on the pollutants present in the water and the final destination. EPA identified and investigated technologies for treating produced water, including aeration, chemical precipitation, reverse osmosis, ion exchange, electrodialysis, thermal distillation, and combination technologies. These technologies reduce or eliminate pollutants in the produced water, allowing beneficial use or surface water discharge.

3.4.1 Aeration

Aeration is primarily used to precipitate (remove) iron from the wastewater, which reduces or eliminates stream bed staining and preserves the aesthetic quality of the receiving stream. The aeration process mixes air and water, typically by injecting air into water, spraying water into the air, or allowing water to pass over an irregular surface. Pollutants are released from the water through oxidation, precipitation, or evaporation. CBM well operators may use spray nozzles, agitators, and bubble diffusers to aerate the water before discharge. Following sedimentation and chemical precipitation, discharges to surface water typically flow over rip-rap to aerate the water before it enters the stream bed, which also helps to reduce erosion and further precipitate pollutants (e.g., iron) from the water.

3.4.2 Sedimentation/Chemical Precipitation

CBM well operators use sedimentation and chemical precipitation to remove suspended solids. Solids settle to the bottom of sedimentation basin and are removed via an underflow pipe. Chemical addition is often used to facilitate solids settling (i.e., chemical precipitation). Sedimentation is not expected to reduce dissolved solids.

This treatment typically occurs prior to discharging the produced water to surface water or a POTW. Numerous operators use sedimentation to remove iron (typically preceded by some form of aeration to facilitate iron settling). EPA also received several questionnaire responses indicating targeted barium removal using chemical precipitation. As discussed in Section 3.3.2, operators often use storage ponds for evaporation/infiltration, where solids will typically settle to some extent.

3.4.3 Reverse Osmosis

Reverse osmosis (RO) separates dissolved solids or other constituents from water by passing the water solution through a semipermeable cellophane-like membrane. RO is a proven treatment process for removing TDS and other constituents such as arsenic. RO has been used extensively to convert brackish water/seawater (brine) to drinking water, to reclaim wastewater, and to recover dissolved salts from various industrial processes.

Although RO membranes can remove dissolved solids, suspended solids need to be removed in pretreatment steps. A high-quality feed water with reduced TSS levels prevents the membrane from plugging. In addition, membrane fouling and scaling will increase the required pressure to maintain a constant flow through the treatment process.

Preliminary responses to the questionnaire indicate RO as the primary desalting membrane process used in produced water treatment. The high-quality water resulting from the RO process could be available for many beneficial uses (ALL, 2003).

In addition to RO, nanofiltration is also a high-pressure desalting membrane process. Microfiltration and ultrafiltration are low-pressure membrane filtration processes that are used to remove solid particles; these are not considered desalting membranes, but are often used in the pretreatment steps.

3.4.4 Ion Exchange

In an ion exchange system (IX), wastewater passes through a system that contains a material (typically a resin) to extract and absorb specific constituents. In a typical setup, a feed stream passes through a column, which holds the resin. Pollutants absorb onto the resin as the feed moves through the system. Eventually the resin becomes saturated with the targeted pollutant requiring regeneration of the resin. A regenerant solution then passes through the column. For cation resins such as for sodium and metals, the regenerant is an acid, and the hydrogen ions in the acid remove the absorbed pollutant from the resin. The sodium and metals concentrations are much higher in the regenerant than in the feed stream. Therefore, the ion-exchange process separates the sodium from the water and results in a concentrated brine stream and a treated produced water stream. Because the salt content of the produced water has been reduced, the treated stream can be discharged to surface waters or beneficially used.

EMIT Water Discharge Technology and LLC Higgins Loop™ – This technology is currently being used in the PRB and is a continuous countercurrent IX system. The EMIT process uses a strong acid cation exchange resin, which removes sodium, barium, calcium, and magnesium ions from the water and exchanges them with hydrogen ions (ALL, 2006a).

Drake Water Technology Process (Drake Process) – This is a proprietary pilot-scale technology using an IX system that selectively removes sodium ions from CBM produced water. The PRB produced water is typically high in sodium (making it the dominant ion) and low in calcium and magnesium, which can yield high SAR values that limit beneficial use. Drake has four patents pending and a fifth in preparation that optimize the design of IX systems to treat PRB produced water. (U.S. EPA, 2009).

3.4.5 Electrodialysis

Similar to RO, electrodialysis (ED) is also considered a desalting membrane (removes dissolved contaminants) but uses an electrically driven process. Electrodialysis uses alternating pairs of cation (positively charged) and anion (negatively charged) membranes positioned between two oppositely charged electrodes. Channeled spacers between the membranes create parallel flow streams across the membrane surface. Water is pumped into the flow channels; when voltage is applied, the electrical current causes ions from the water to migrate toward the oppositely charged electrodes and are restrained in the polarized membranes (Malmrose et al., 2004).

3.4.6 Thermal Distillation

EPA observed a proprietary thermal distillation process to treat produced water prior to discharge to a POTW in the San Juan basin. The AltelaRain® system is a transportable and fully integrated water thermal distillation treatment system for both CBM and conventional produced water. The system is built and contained in standard 20-foot or 45-foot shipping containers and transported by truck to individual well sites. The AltelaRain® system concentrates TDS into a brine waste stream and discharges water with very low TDS concentrations.

3.4.7 Multiple Technology Applications

EPA observed pilot-scale treatment facilities that integrate several treatment technologies to reduce pollutant concentrations so that water can be beneficially used or discharged. One pilot plant was run by an operator in conjunction with Sandia National Laboratories and New Mexico State University. The system used separators, ultrafiltration, and RO to treat produced water prior to beneficial use.

EPA also observed a pilot plant run by Triwatech, consisting of a portable, pilot treatment system that included “off-the-shelf” equipment as well as proprietary, patent-pending treatment technologies. This system has been pilot tested for several operators in the San Juan Basin. The Triwatech pilot plant is located in a portable truck trailer and can be moved to different well sites. The system is used to determine the optimal treatment configuration for a specific CBM water quality. Triwatech typically requires about two to four weeks of study to determine an optimal design for a full-scale system. The final Triwatech process design consists of pre-treatment, polishing treatment, and post-treatment, which may consist of technologies such as filtration, sedimentation, nanofiltration, RO, IX, or activated carbon. There are several different treatment steps that are evaluated during the initial pilot testing, and the final treatment system comprises a mix of the different types of treatment.

3.5 Current Economics of CBM Production

CBM is a form of natural gas and therefore is included in the accounting of U.S. natural gas reserves and production. However, because of differences in CBM geological formations and production characteristics, the economics of CBM production and other natural gas (conventional gas) or oil production differ, as discussed below.

As noted in Section 3.1, CBM is generally produced from relatively shallow coalbeds. These coalbeds underlie the surface in broad areas, often covering many hundreds of square miles. Large amounts of produced water are typically generated initially; over time, the amount of water produced generally diminishes. In contrast, conventional gas is often contained within sharply defined geological formations, which can be accessed only from a relatively small area using deeper wells, typically, than those required for CBM production. Extracting conventional gas often generates relatively little water at first, but the production of water can increase over time. These differences in production between conventional gas and CBM lead to a very different economic profile in terms of production economics and, in some cases, firm economics. Because produced water management costs are a significant portion of operating costs in either type of gas production (U.S. DOE EIA, 2010e), CBM projects often begin with high operating costs that tend to diminish over time, while operating costs for conventional oil and gas often rise over time.

3.5.1 Number of Wells and Projects

CBM wells are rarely operated as single units responsible for their own production costs, because operators realize economies of scale in operating several wells together as an economic unit. Given that CBM production requires numerous wells distributed over the coalbed, operators tend to include a large number of wells in each economic production unit, or project.

In conventional oil and gas production, where the productive geographic area of an oil/gas producing formation is typically constrained, an economic production unit is often a lease. A lease usually comprises a relatively small number of wells ganged to a tank battery. In the tanks, water is separated and the oil and/or gas is prepared for sale and delivered to the market by pipeline (oil and gas) or truck (usually only oil). Produced water from that group of wells is piped to an underground injection well(s) located on the lease or nearby. Alternatively, the produced water might be trucked to a commercial disposal facility. The costs of produced water disposal are also shared among the group of wells.

For CBM production, however, the economic production unit can be much larger than a lease, and the concept of “project” is more applicable. A project can be as small as a single well or a lease with just a few wells, but it can also be as large as over 1,000 wells. The tendency toward large projects is due to the wide geographic area in which a coalbed might be located. Projects in the discharging basins tend to be larger than projects in zero discharge basins.

According to EPA's screener survey,[13] a total of about 56,000 CBM wells, organized into approximately 750 projects, produced gas and/or water in 2008.[14] Of these projects, a minority (approximately 180 projects) discharged some produced water. Table 3-10 and Table 3-11 characterize the numbers of wells and projects reported in the questionnaire. As Table 3-10 shows, most of these wells are located in the PRB (21,000, or 38 percent). The zero discharge basins have a relatively small number of wells (18,600 or 33 percent) but account for about 50 percent of production, because average production per well is greater in the zero discharge basins than in the discharging basins. Table 3-11 also presents information on gas produced by discharging and zero discharge projects in each basin. As the table shows, projects that discharged at least some produced water to surface waters averaged gas production of 27 million cubic feet (MMcf) per well and 4.4 Bcf per project in 2008, while those that discharged no produced water averaged greater gas production per well (45 MMcf) but lower production per project (2.1 Bcf) than projects discharging to surface waters. The higher per-project production in discharging basins results from the higher average number of wells per project in the discharging basins.

Table 3-10. Wells and Projects by Discharging and Zero Discharge Basins

Basin	Number of Wells	Percentage of Total Wells	Number of Projects	Average Wells per Project
Discharging Basins				
PRB	21,000	38%	220	100
Green River	3,700	7%	5	750
Raton	320	1%	15	25
Black Warrior	5,200	9%	15	350
Cahaba	400	1%	2	200
Appalachian/Illinois	6,200	11%	30	200
Total Wells (Discharging Basins)	37,000	66%	280	130
Zero Discharge Basins				
San Juan	7,000	13%	200	35
Uinta-Piceance	1,000	2%	15	80
Anadarko	2,800	5%	35	80
Arkoma	2,400	4%	180	15
Cherokee/Forest City	5,300	9%	40	130
Other	80	0%	4	20
Total Wells (Zero Discharge Basins)	18,600	33%	474	40
Total Wells, U.S.	**56,000**		**750**	**75**

Source: U.S. EPA, 2010a.
Note: Unless less than 5, all numbers are rounded to nearest 5, 10, or 100. Totals are independently rounded.

[13] See (ERG, 2010) for how the data presented here were modified to protect CBI.

[14] Because wells can produce water before producing gas, screener respondents were asked to report numbers of wells that were producing either water or gas.

Table 3-11. Characteristics of Discharging vs. Zero Discharge Projects

Type of Project	Number of Wells	Number of Projects	Gas Produced (2008) (Bcf)	Wells per Project	Gas per Well (MMcf)	Gas per Project (Bcf)
Discharging Projects						
PRB	17,600	150	512	120	29	3.4
Green River	80	3	7	30	87	2.3
Raton	2,800	3	99	930	35	32.8
Black Warrior	5,100	15	104	400	20	8.0
Cahaba	400	2	4	200	10	1.9
Appalachian and IL	3,400	10	80	300	24	7.3
Total Discharging Projects	29,300	180	805	160	27	4.4
Zero Discharge Projects Operating Within Discharging Basins [a]						
PRB	3,700	70	95	50	26	1.4
Green River	250	10	6	25	27	0.6
Raton	950	2	30	475	32	15.1
Black Warrior	15	1	<1	15	28	0.4
Appalachian and IL	2,800	20	64	150	23	3.4
Total Zero Discharge Projects in Discharging Basins	7,700	100	196	75	26	1.9
Zero Discharge Projects Operating Within Zero Discharge Basins						
San Juan	7,000	200	755	35	107	3.8
Cherokee/Forest City	5,300	40	79	130	15	2.0
Uinta-Piceance	1,000	15	65	80	64	5.0
Arkoma	2,400	180	66	15	28	0.4
Anadarko	2,800	35	18	80	6	0.5
Other	70	4	3	20	48	0.9
Total Zero Discharge Projects in Zero Discharge Basins	18,600	470	987	40	53	2.1
Total Zero Discharge Projects, All Basins	26,200	570	1,183	45	45	2.1
Total, U.S.	**56,000**	**750**	**1,988**	**75**	**36**	**2.6**

Source: U.S. EPA, 2010a.
Note: Most numbers are rounded to nearest 5, 10, 100, or 1,000, unless less than 5. Totals are independently rounded.
a – A discharging basin is defined as one that has at least one discharging project operating within it. However, zero discharge projects may also be operational within these basins as well.

3.5.2 Financial Characteristics of CBM Projects

As with any business, CBM project revenues received must cover the costs of production or it is not economical to produce the project. Additionally, for planned projects not yet constructed, the estimated operating cash flow over time must be able to cover all of the costs of the project from inception to end of life. Operating cash flow is revenues to all of the working interest owners minus their combined share of the costs of production, including produced water management costs over the assumed production lifetime of the project. The cash flow must be positive over this time frame and must also cover the projected investment costs (e.g., costs of preparing the site, drilling the wells, constructing and installing the production (including produced water management) infrastructure, as well as provide some return to the investors to cover the cost of capital[15] and risk (new oil and gas ventures of any type are risky investments). If the operating cash flow over the estimated project operating life is not expected to cover the investment costs with a reasonable return to investors, the project will not be undertaken.

Once a project is constructed and begins operating, it will continue to be operated as long as cash flow is positive (allowing for possibly a few years of negative cash flow initially as the coalbed is dewatered and potentially little gas is produced). Thus, key financial characteristics of existing CBM projects are project revenues and production costs (including produced water management). The key financial characteristics of new CBM projects include the total investment costs of the project, as well as the annually occurring revenues and production costs.

3.5.2.1 Project Revenues

Project revenues depend on the amount of gas produced from the project and the price received for that gas. Using preliminary EPA questionnaire responses, EPA was able to approximate the average revenues per project that were likely to have been earned, by basin, using the wellhead price of gas from publicly available sources and production volumes reported in EPA's screener survey. Wellhead price is the price received by the interest owners at the wellhead (that is, net of additional gathering, transportation, and other costs which reduce the price from that seen at the major gas gathering hubs). The U.S. Department of Energy's EIA (US U.S. DOE EIA 2010c) provides the average wellhead prices for gas in 2008 by state for most oil and gas producing states.

Table 3-12 presents average wellhead prices received in 2008 in some of the key CBM basin states. These prices range from a high of $9.65 per thousand cubic feet (Mcf) in Alabama to a low of $6.94 per Mcf (New Mexico, Colorado). The high wellhead price in Alabama results in part from the state's proximity to Henry Hub, which is the major gas distribution hub and pricing point for gas futures in the United States. This hub, which is the intersection of a number of large pipelines, is located in Louisiana. The higher the transportation cost, the lower the wellhead price received by the operators. Because transport costs from states located near Louisiana are much lower than those from the Rocky Mountain area, the average wellhead price in Texas, Louisiana, and Alabama is much higher than in the Rocky Mountain states.

Table 3-12. 2008 Wellhead Prices ($/Mcf)

Basin	Wellhead Price ($/Mcf)	State Wellhead Price Used
Anadarko	$7.96	OK
Appalachian [a]	$7.96	U.S.
Illinois	$7.96	U.S.
Arkoma	$7.96	OK
Black Warrior	$9.65	AL

[15] For example, borrowing money has a cost, expressed as interest payments.

Table 3-12. 2008 Wellhead Prices ($/Mcf)

Basin	Wellhead Price ($/Mcf)	State Wellhead Price Used
Cahaba	$9.65	AL
Cherokee/Forest City	$8.40	KS
Green River	$6.94	CO
Arkla	$8.73	LA
Permian/Ft. Worth	$8.51	TX
Wind River	$6.86	WY
Powder River	$6.86	WY
Raton	$6.94	CO
San Juan	$6.94	NM
Uinta-Piceance	$6.94	CO

Source: U.S. DOE EIA, 2010c.
a – Individual prices by state were not available.

EPA multiplied the relevant questionnaire responses for gas production in each basin (see Table 3-2) and per project (see Table 3-11) by the relevant wellhead price in each basin shown in Table 3-12. In this way, EPA estimated the total 2008 gross revenues (revenues to all interests) associated with CBM production nationally, for each basin, and per project in each basin (see Table 3-13).

Table 3-13. 2008 Estimated Gross Revenues ($millions) by Basin, Discharging Basins vs. Zero Discharge Basins

Basin	Gross Revenues/Project	Total Gross Revenues by Basin
Discharging Basins		
PRB	$19	$4,163
Green River	$7	$93
Raton	$179	$893
Black Warrior	$72	$1,006
Cahaba	$18	$36
Appalachian and IL	$38	$1,146
Discharging Basins Average/Total	$26	$7,338
Zero Discharge Basins		
San Juan	$26	$5,241
Cherokee/Forest City	$17	$662
Uinta-Piceance	$35	$453
Arkoma	$3	$528
Anadarko	$4	$144
Other	$6	$26
Zero Discharge Basins Average/Total	$15	$7,054

Source: EPA estimates (see text).

In 2008, EPA estimates that total gross revenues for CBM were about $14 billion. Of these revenues, approximately $7.3 billion (51 percent) was generated in discharging basins and approximately $7 billion (49 percent) was generated in zero discharge basins. Average revenues per project over all projects were estimated to be about $21 million. In discharging basins, average revenues per project were estimated to be about $26 million and in zero discharge basins, average revenues per project were estimated to be about $15 million.

Note that these estimated revenues are gross revenues that are shared among working interest operators, royalty owners, and state and local governments. Typical royalty payments might range from 10 to 20 percent of gross revenues; state and local taxes might consume several additional percentages. Thus the percentage of revenues received by all working interest operators (including a 100 percent interest owner) might be less than 80 percent of the gross project revenues. .

The per-project estimated gross revenues range from $3 million per project in the Arkoma Basin (where number of wells per project tends to be smaller) up to $179 million per project in the Green River Basin (where number of wells per project are among the highest).

Table 3-14 presents similar gross revenue information, but identifies the estimated average gross revenues per project depending on whether the projects are discharging or zero discharge projects. For discharging projects, the average gross revenues per project in 2008 were estimated to be about $33 million, whereas for zero discharge projects, the average gross revenues per project were estimated to be about $15 million. There are more than three times as many wells, on average, at discharging projects than at zero discharge projects (see Table 3-11), which explains much of the difference in estimated average revenues per project between discharging and zero discharge basins and projects. Given that the amount of gas produced per well at discharging projects tends to be lower on average than the amount of gas produced per well at zero discharge project (and thus revenues per well are likely to be lower), the size of the projects is most likely the major factor in this difference (see Table 3-11).

Table 3-14. Estimated 2008 Gross Revenues ($millions) by Basin, Discharging Projects vs. Zero Discharge Projects

Basin	Average Gross Revenues/Project	Total Gross Revenues by Basin
Discharging Projects		
PRB	$24	$3,513
Green River	$16	$49
Raton	$228	$684
Black Warrior	$77	$1,002
Cahaba	$18	$36
Appalachian and IL	$58	$636
Discharging Projects Average/Total	$33	$5,920
Zero Discharge Projects		
PRB	$9	$650
Green River	$4	$45
Raton	$105	$209

Table 3-14. Estimated 2008 Gross Revenues ($millions) by Basin, Discharging Projects vs. Zero Discharge Projects

Basin	Average Gross Revenues/Project	Total Gross Revenues by Basin
Black Warrior	$4	$4
Appalachian and IL	$27	$510
San Juan	$26	$5,241
Cherokee/Forest City	$17	$662
Uinta-Piceance	$35	$453
Arkoma	$3	$528
Anadarko	$4	$144
Other	$6	$26
Zero Discharge Projects Average/Total	$15	$8,473

Source: EPA estimates (see text).

Note that wellhead prices can be slightly less at CBM projects on average than at conventional oil and gas leases because CBM projects are sometimes located in areas with less developed pipeline infrastructure (and therefore greater transportation costs). However, this is becoming a less important issue. In recent years, several pipelines have been constructed in the Rocky Mountain area, which has historically been underserved. Two of these pipelines, the Cheyenne Plains Pipeline and the Rockies Express Pipeline, have substantially increased transport capacity in Colorado and Wyoming. The Colorado Interstate Pipeline Company's Cheyenne Plains Pipeline, which was built in 2004 and has the capacity to transport over 730 MMcf per day, transports natural gas from production sites in these states to southwestern Kansas through an interconnection with Northern Natural Gas and Natural Gas Pipeline Company of America (U.S. DOE EIA, 2010d). The largest boost to carrying capacity in the Rockies region, however, was the addition of the Rockies Express Pipeline System, with a 1.8 Bcf/day capacity. The second segment of the pipeline was placed in service in 2007 and was fully operational in November 2009, becoming the first direct transport from the Rocky Mountain region to the Midwest and Northeast (KinderMorgan, 2010).

Due to increasing access to pipelines with sufficient capacity, EPA believes the average wellhead prices used in these estimates reasonably approximate prices received by CBM projects in 2008 and do not substantially overstate average 2008 revenues reported in this profile of CBM project finances.

It is, however, important to note that 2008 wellhead gas prices were at an historic high. In 2009, the price of gas dropped substantially. The U.S. average dropped from $7.96 per Mcf to $3.71 per Mcf, a 53-percent reduction (U.S. DOE EIA, 2010c). Therefore, average revenue per project in 2009 also are expected to have declined substantially, although the exact declines are difficult to estimate given expected production declines from existing wells combined with additions to production from new wells at CBM projects. Section 3.6 discusses wellhead price trends in more detail.

3.5.2.2 Project Costs

Balanced against the estimated project revenues are the total investment costs of the project and gas production costs. Total investment costs include costs to acquire leases, prepare the site, drill wells, and construct and install production equipment and piping. Gas production costs include energy and labor costs to extract the gas and produced water management costs, including treatment and disposal.

EPA's detailed questionnaire data on production costs are not yet available. However, U.S. DOE EIA (2010e) provides a cost study of four primary CBM basins, including the Appalachian, Black Warrior, Powder River, and San Juan Basins. In this cost study, EIA characterizes 10-well leases dewatered by artificial lift (that is, using pumping systems, rather than natural flow) for each of the four basins. Table 3-15 presents the basic assumptions used in their costing assumptions for each of these leases (a 10-well lease in these basins is generally smaller than a typical project, as defined in EPA's surveys, in most cases). As this table shows, the PRB is modeled as having leases with the shallowest wells, a moderate level of gas production per well, and the highest produced water production per well among the four basins investigated. San Juan leases are modeled assuming the deepest wells, highest gas production per well, and a relatively modest water production per well. Leases in the Appalachian Basin are assumed to have the least-productive wells. Black Warrior is a moderate case in all categories.

Table 3-15. Assumptions Used in U.S. DOE EIA Cost Models for Four Key CBM Basins

Basin	Well Depth (ft)	Dewatering Method	Per Well	
			Gas Production (Mcf/day)	Water Production (barrels/day)
Appalachian	2,000	Sucker Rod	60	20
Black Warrior	2,000	Sucker Rod	100	43
PRB	1,000	Submersible	100	300
San Juan	3,000	Sucker Rod	500	20

Source: U.S. DOE EIA, 2010e.

Based on these assumptions, U.S. DOE EIA (2010e) estimated two major cost categories associated with CBM production: equipment costs and operating and maintenance (O&M) costs. These costs are developed for the assumed 10-well leases in each of the four basins for 2002 and 2006 through 2009 to assist in developing cost indices for CBM production. Table 3-16. summarizes these cost estimates for 2008 by basin. As the table shows, O&M costs are the lowest in the Appalachian Basin and highest in the San Juan Basin, while equipment costs are lowest in the Powder River Basin and highest in the San Juan Basin. U.S. DOE EIA (2010e) notes that produced water management costs make up a large portion of the estimated operating costs. Therefore, the high operating costs (as well as high equipment costs) seen in San Juan Basin are, in part, driven by the costs of the zero discharge management practices used there (injection, which drives both equipment and operating costs, and commercial disposal), even though volumes of produced water generated per well are relatively low. The relatively high operating costs in PRB are likely caused by managing the high volumes of produced water generated per well. Lower volumes of produced water per well in the Appalachian might help keep the operating costs in that basin low, while the predominance of surface water discharge in the Black Warrior Basin might explain the more moderate operating costs estimated by U.S. DOE EIA in that basin.

Table 3-16. Operating Costs and Costs of Equipment Assuming a 10-Well Lease in Four Key CBM Basins (2008)

Costs ($2008)	Basin			
	Appalachian	**Black Warrior**	**PRB**	**San Juan**
Equipment				
Producing Equipment	$383,700	$426,700	$171,000	$868,700
Gathering Lines	$218,000	$170,800	$237,100	$48,500
Lease Equipment	$323,400	$443,100	$296,700	$373,500
Total Equipment	**$925,100**	**$1,040,600**	**$704,800**	**$1,290,700**
Operating and Maintenance				
Normal Daily Expense	$32,300	$53,000	$48,300	$130,000
Surface Maintenance	$43,800	$40,700	$37,000	$36,800
Subsurface Maintenance	$11,700	$41,500	$86,600	$46,200
Total O&M	**$87,800**	**$135,200**	**$171,900**	**$213,000**

Source: U.S. DOE EIA, 2010e. Assumptions used in these cost estimates appear in Table 3-15.

3.5.3 Operators of CBM Projects

3.5.3.1 Numbers, Size, and Discharge Status of CBM Operators

Operators of any type of oil or gas project can be classified as either majors or independents. *Majors* are large, vertically integrated firms (i.e., they own production, distribution, and/or wholesale or retail distribution facilities). Generally, majors have the easily recognizable names associated with oil and gas production (e.g., Chevron, ConocoPhillips, Marathon), because these companies often own retail distribution firms. *Independents* focus primarily on the upstream activities associated with production. Most CBM operators are independents, but a few majors are involved in CBM production, including Chevron, ConocoPhillips, Marathon, EQT Corporation, Suncor Energy, Inc., and Williams Companies.[16]

EPA's screener survey indicates that there were 252 operators of CBM projects in the United States in 2008 (U.S. EPA, 2010a). Operators of CBM projects can be the owners of the project or contract operators. Owner operators own some portion of the project, known as a "working interest," which can range from 100 percent to a small fraction of the project. In this situation, the operator is responsible for a share of the cost, but also receives the an equivalent share of production and the resulting revenues. As noted earlier, even when an operator owns 100 percent of the working interest, the operator does not own all production (and revenues) from a project. The nonworking interest owners (also known as owners of passive interests) also share in the production, but do not share in any of the costs of production. Nonworking interest

[16] Several sources identify majors, but they do not always agree on who is a major. Generally, majors are defined as large multinational firms with significant ownership of both upstream (production) and downstream (refining, distribution) assets. For this profile, ERG used Yahoo Finance (2010) and Reuters (2010). DOE also defines majors, but their definition is more related to size than to integration.

owners include the mineral rights owners, who receive royalties. Additionally, state and local taxes on production are usually expressed in terms of a share of production (e.g., severance or ad valorem taxes), which also reduce the portion of production received by the working interest owner(s).

Contract operators, on the other hand, share none of the production or costs but are paid to operate the project for the working interest owners. This situation can happen when, for example, a working interest owner comprises a group of investors who themselves are not familiar with the production process. A preliminary investigation of EPA's detailed survey questionnaire responses indicates that relatively few CBM operators are strictly contract operators.

Another important distinguishing feature of CBM operators is whether they are small businesses, as defined by the Small Business Administration (SBA). EPA's screener survey asked operators to self-identify as small or large businesses, using the SBA definitions of small business based on the type of business associated with their firm's major source of income at the highest corporate level (e.g., a parent company). Most of the CBM operators are likely to be in the oil and gas production or well drilling industries (NAICS 211111 or 213111). Small firms in these industries must have fewer than 500 employees. For other industries (e.g., oil and gas support activities [NAICS 213112], which would include contract operators), small firms must have less than $7 million in revenues (SBA, 2008).

Eight operators claimed that their screener survey responses included confidential information on the size of the firm (which could not be replaced with public data), which precludes using their responses in the discussion that follows. Thus, any discussion on size of firms focuses on 244 operators whose data can be released. According to the screener survey responses, 194 operators were small businesses and 50 operators were large businesses. Of these 244 operators, the large majority was small operators with zero discharge projects (162 of 244, or 68 percent). Only 32 small operators operate discharging projects. Table 3-17 summarizes the numbers of small and large operators and the discharge status of their projects.

Table 3-17. Number of CBM Operators by Size of Firm

Discharge Status	**Large**	**Small**	**Total**
Discharging	21	32	**55**
Zero Discharge Only	29	162	**197**
Total [a]	**50**	**194**	**252**

Source: U.S. EPA, 2010a.
a – The number of large and small operators by discharge status does not add to totals because eight operators are not included in the business size columns for CBI reasons, although their discharge status is not CBI.

The discharge status of the eight CBI operators can be discussed, and EPA included these operators in Table 3-18. [17] Two CBI operators operate discharging projects and the other six operate only zero discharge projects. With these operators added in, 55 of 252 total operators (22 percent) operate discharging projects..

[17] Discharge status, even if claimed CBI, is not considered by EPA to be information subject to claims of confidentiality.

Table 3-18 provides the numbers of operators by their basin location and discharge status. Note this table double-counts a number of operators because many operators have projects in multiple basins, so overall totals for dischargers and nondischargers are not shown.

Table 3-18. Numbers of Operators by Discharge Status and Basin

Basin	Discharging Operators [a]	Zero Discharge Operators Only	Total
PRB	35	29	**64**
Green River	3	5	**8**
Raton	3	2	**5**
Black Warrior	7	1	**8**
Cahaba	3	0	**3**
Appalachian and IL	6	10	**16**
San Juan	0	56	**56**
Cherokee/Forest City	0	36	**36**
Uinta-Piceance	0	9	**9**
Arkoma	0	41	**41**
Anadarko	0	32	**32**
Other	0	4	**4**

Source: U.S. EPA, 2010a.
a – Operators with at least one project in that basin directly or indirectly discharging at least some produced water to surface water.

3.5.3.2 Financial Characteristics of Firms Producing CBM

Table 3-19 summarizes key financial data from 2008 for public CBM firms using a compilation of financial information from nearly all publicly held U.S. oil and gas producing firms prepared by *Oil & Gas Journal* (OGJ, 2009). These firms are known as the OGJ 150 and the data on these firms also provide general financial benchmarks for the oil and gas industry for comparison to the CBM industry subset. EPA identified those firms among the OGJ 150 operating or owning CBM wells and extracted their financial data. EPA added several additional foreign-owned or other firms that were not included in the OGJ compilation to Table 3-19 by extracting financial information from 20-F or 10-K forms available from the SEC. The year 2008 is generally considered to be a better year for the oil and gas industry financially than 2009, due to higher gas prices realized during 2008 than 2009 (see Section 3.6.2), particularly in the first half of the year. However, as noted in the OGJ report (OGJ, 2009), despite increases in revenues, profits slid in the latter half of 2008 as prices and demand fell (OGJ, 2009), heading toward the low prices seen in 2009.

EPA identified 34 publicly held firms that operate or own firms with CBM projects (and therefore are parent corporations). A few own more than one CBM operator. Of these 34 firms, seven are majors, 16 are large independents, and 11 are small independents (small defined by the SBA). A total of 16 firms are associated with firms that operate discharging projects; 18 are, or are associated with, firms that operate only zero discharge projects.

Table 3-19 indicates that majors and large independents in both groups (discharging and zero discharge) generally had positive net income. However, despite the high gas prices in 2008, net income results for most small independents were poor. Only four small independents (all dischargers) in the publicly held group had positive net income in 2008.

Table 3-19. Key Financial Information for Publicly Held CBM Firms (2008)

Firms	Total Revenues ($millions)	Net Income ($millions)	Total Assets ($millions)	Total Equity ($millions)	Total Liabilities ($millions)
Firms Owning Discharging Projects					
Majors					
Chevron U.S.A.	$273,005	$23,931	$161,165	$86,648	$74,517
Suncor	$28,637	$2,487	$32,528	$14,523	$18,005
The Williams Companies	$3,121	$1,260	$10,286	NA	NA
Large Independents					
Anadarko	$15,723	$3,261	$48,923	$18,795	$30,128
Devon	$15,211	-$2,148	$31,908	$17,060	$14,848
El Paso	$5,363	-$823	$23,668	$4,035	$19,633
Energen	$1,569	$322	$3,775	$1,913	$1,862
Fidelity Exploration	$712	$122	$1,793	NA	NA
Range Resources	$1,323	$346	$5,563	$2,458	$3,105
XTO [a]	$7,695	$1,912	$38,254	$17,347	$20,907
Small Independents					
Bill Barrett	$620	$108	$1,995	$1,088	$907
Belden & Blake	$158	-$29	$669	$77	$593
Continental Production Company	$960	$321	$2,216	$949	$1,267
Double Eagle Petroleum	$50	$10	$172	$55	$117
GeoMet	$69	-$22	$37,	$192	$185
Penn Virginia	$1,221	$124	$2,997	$1,019	$1,978
Firms Owning Only Zero Discharge Projects					
Majors [b]					
BP America	$367,053	$21,666	$228,238	$92,109	$136,129
ConocoPhillips	$246,182	-$16,998	$142,865	$55,165	$87,700
EQT	$457	$253	$2,338	NA	NA
Marathon Oil	$78,569	$3,528	$42,686	$21,409	$21,277
Large Independents					
Chesapeake	$11,629	$723	$38,444	$16,297	$22,147
CNX	$789	$239	$2,125	$1,385	$740
Dominion	$4,312	$468	$11,100	NA	NA
Layne Christianson	$1,008	$27	$719	$456	$263
Newfield	$2,225	-$373	$7,305	$3,257	$4,048
Noble Energy	$3,901	$1,350	$12,384	$6,309	$6,075
Southwestern Energy	$2,312	$568	$4,7608	$2,508	$2,2528
St. Mary Land & Exploration	$1,302	$92	$2,695	$1,127	$1,568

Table 3-19. Key Financial Information for Publicly Held CBM Firms (2008)

Firms	Total Revenues ($millions)	Net Income ($millions)	Total Assets ($millions)	Total Equity ($millions)	Total Liabilities ($millions)
Unit Petroleum	$1,358	$144	$2,582	$1,633	$949
Small Independents					
Enerjex	$4	-$5	$118	$1	$9
Petrohawk	$1,095	-$388	$6,907	$3,405	$3,502
PetroQuest	$314	-$97	$670	$237	$433
Rosetta Resources	$501	-$188	$1,154	$726	$428
Warren Resources	$109	-$242	$287	$112	$175

Source: OGJ, 2009; GeoMet, 2009; Suncor, 2009, BP, 2009; Reuters, 2010, Yahoo Finance, 2010. One company was eliminated as a major using corporate websites indicating that they considered themselves independents (Southwest Energy).
a – XTO was acquired by ExxonMobil in 2010. In 2008, it was considered an independent.
b – Majors were identified using Reuters, 2010, and Yahoo Finance, 2010, along with information on corporate websites indicating an integration or independent.
NA – Not available.

The magnitude of these losses can be gauged using financial ratios. Financial ratios allow various financial items to be compared across firms or to be compared to a benchmark, such as industry averages. They are routinely used by financial analysts, investment firms, and financial rating organizations to judge firm financial health and to consider investments in the companies under review. The data available from OGJ are limited, but do allow some assessments of profitability and debt loads.

EPA compared three key financial ratios for public CBM firms for 2008 to the overall 2008 average ratios (where available) from all public oil and gas firms listed in OGJ (2009). Two ratios indicate profitability—return on assets (ROA) and net profit margin—and one assesses debt (debt-to-asset ratio).

ROA is defined as net income divided by assets. It reflects the ability of an investment to generate income and whether the investment is reasonable given other possible returns on investments of similar risk. These returns can be compared to returns on the stock market (a somewhat risky investment) or the percent interest from interest-bearing accounts (relatively low-risk investments) to determine whether the returns seem good or poor compared to other possible investments.

Net profit margin is computed as net income divided by revenues. This ratio can indicate how well a company controls costs, but more importantly, how well a company might weather an economic downturn. Those firms with net losses or low profit ratios in 2008 were at a greater risk of continued, deeper losses, or at risk of crossing over into losses in 2009, as gas prices continued their drop. A “good” profit margin in one industry might not be a “good” profit margin in another, and profit margins need to be compared to averages for the industry.

Table 3-20. Key Financial Ratios for Public CBM Firms Compared to the OGJ 150 (2008)

Firm Size	Return on Assets	Net Profit Margin	Net Profit Margin Among Profitable	Debt to Asset
CBM Operators				
Firms With Discharging Projects				
Major	13.57%	9.08%	9.08%	47.77%
Large Independent	1.94%	6.29%	22.07%	59.49%
Small Independent	6.07%	16.62%	19.73%	59.90%
Firms With Only Zero Discharge Projects				
Major	2.03%	1.22%	5.70%	59.23%
Large Independent	3.94%	11.22%	13.56%	53.57%
Small Independent	-10.18%	-45.45%	NA	50.36%
OGJ 150 [a]				
Major	10.19%	6.00%	7.63%	52.51%
Large Independent	1.27%	3.22%	14.97%	57.26%
Small Independent	-5.77%	-14.19%	31.68%	59.48%

Source: Reuters, 2010; Yahoo Finance, 2010; OGJ, 2009; see Table 3-19.
a – Majors were identified using Reuters, 2010, and Yahoo Finance, 2010, along with information on corporate websites indicating an integration or independent status in calculating ratios for the OGJ 150. Firms not classified as majors with assets above $2 billion were used to construct ratios for large independents. The remaining firms were considered small independents.
NA – Not available

The third ratio, the debt to asset ratio is calculated as total liability divided by total assets. It measures the ability of companies to take on more debt and whether they could be in difficulty if creditors began calling in debts. Very high debt-to-asset ratios indicate highly leveraged firms, which might have trouble finding additional capital or have potential for corporate takeover. Very low ratios, however, could mean that the firm is not taking advantage of leverage for growth. Assessing debt-to-asset ratios should take into account how the industry as a whole operates. Those with much higher debt-to-asset ratios than is typical for the industry might be less resilient in a downturn, whereas those with much lower ratios, while less likely to fail, might not be growing as quickly as they could.

Table 3-20 presents these three ratios for the public CBM firms as compared to the Oil & Gas industry. As the table shows, CBM firms with discharging projects, regardless of size, generally appear to have higher profit margins (that is, they were more profitable) and better ROA in 2008 than similar-sized firms that operate only zero discharge projects (except for large independents). Because of large losses for some firms, which tended to overwhelm the averages, EPA also calculated profit margins over those firms that reported positive net income. When the profit margin was calculated only over those firms with positive net income, firms with discharging projects still appeared to have been more profitable, on average, than similar firms with zero discharge projects (including large independents). Furthermore, for the most part, firms with discharging projects had similar to better profitability and ROAs than similar-sized firms among the OGJ 150. Firms with zero discharge projects (except for large independents) tended, on average, to perform worse than the OGJ firms on net profit and ROA. These firms with zero discharge projects, however, would not be affected by any changes to requirements for managing produced water from CBM projects.

In terms of debt loads, firms with discharging projects on average had similar debt-to-asset ratios as the overall OGJ 150, although majors with discharging projects tended to be less leveraged than average, but not substantially so. A ratio under 50 percent indicates a firm that uses equity more than debt to fund capital expenditures. Among the firms with zero discharge projects, the majors were, on average, more leveraged, but the remaining firm sizes tended to have lower than average debt-to-asset ratios than the OGJ 150. Therefore, on average, the publicly held CBM firms are not excessively leveraged compared to the overall industry.

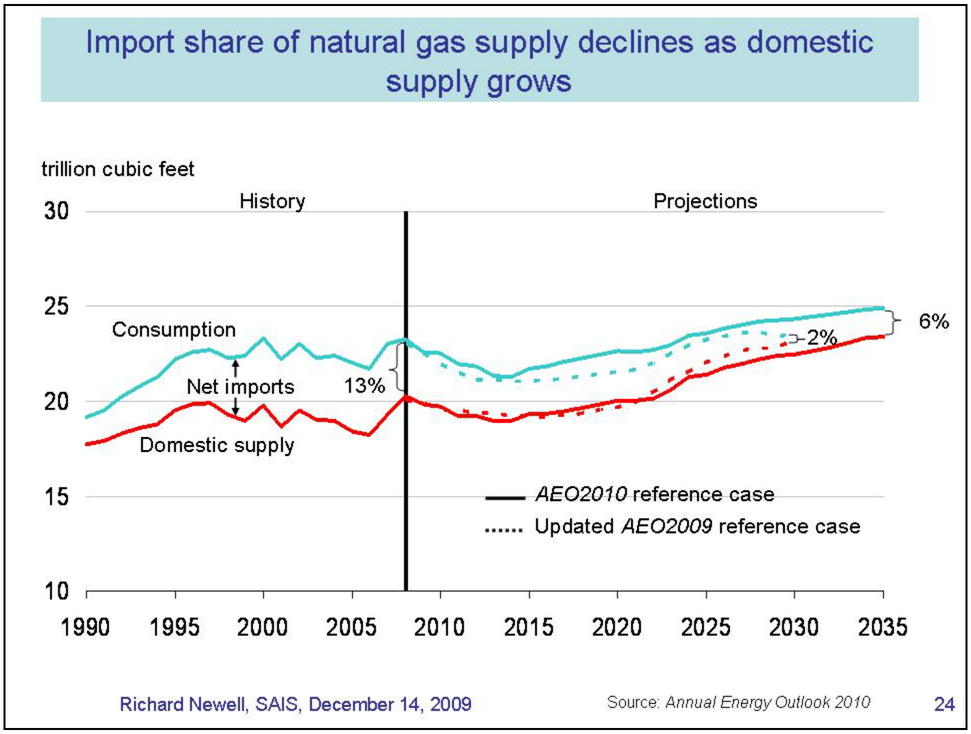
3.6 Trends and Projections

This section discusses the future economics of CBM production, including national-level production trends, wellhead gas price projections, and factors affecting the costs of production that could change over time, and the potential for the reserves of CBM in the currently developed basins to be produced in the future. These types of information are critical for determining the overall economics of a depletable resource such as CBM.

3.6.1 The Present and Future of CBM

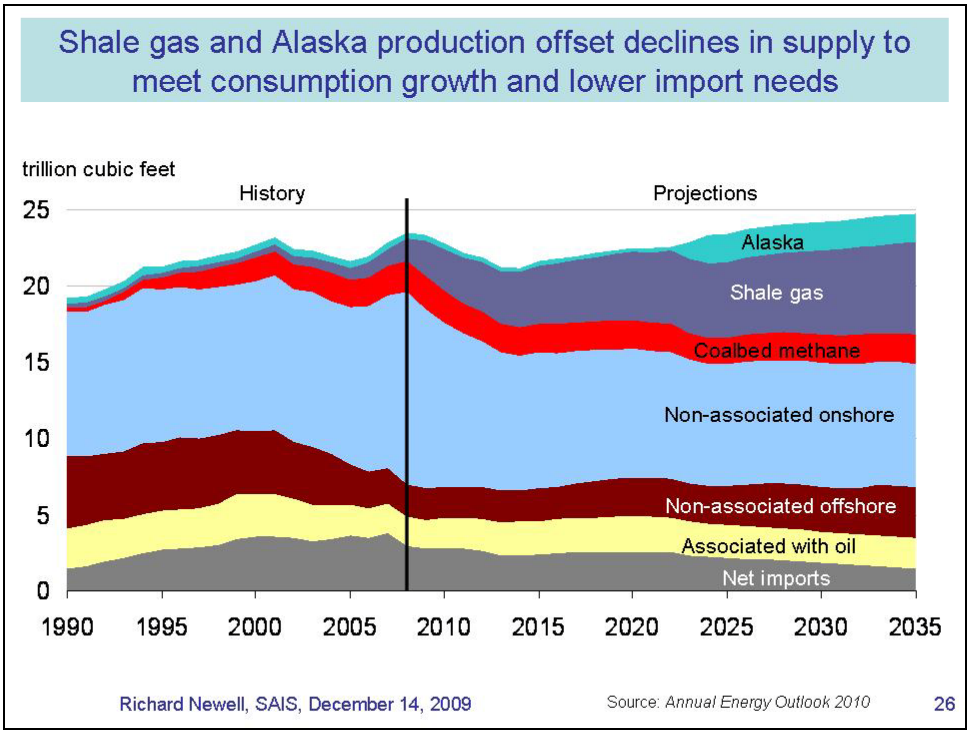
U.S. DOE EIA indicates that 2008 was a recent-year peak in domestic production and consumption of natural gas (including CBM) (U.S. DOE EIA, 2010e). However, in 2009, both production and consumption of natural gas fell. Production by type of natural gas is not yet available for 2009, so it is not possible to determine from U.S. DOE EIA data if CBM production also declined in 2009. However, the Wyoming Oil and Gas Conservation Commission (WOGCC) data indicate that production of CBM in the Wyoming portion of the PRB (by far the most productive portion of the basin and a major contributor to total CBM production in the United States) rose between 2008 and 2009 (WOGCC, 2010). EIA predicts a continuing decline in both domestic production and consumption of all natural gas for the next several years. By around 2015, consumption and domestic production will again begin to rise gently, with production slightly closing the gap with consumption and reducing imports. Figure 3-3 shows EIA’s predictions for the consumption and production of natural gas.

U.S. DOE EIA (2010e) also predicts that CBM production will remain roughly steady through 2035, despite the overall fall in production of natural gas predicted over the next few years. In the longer term, however, natural gas production of all types is expected to rise, contributing to a slight decline in the percentage of natural gas attributable to CBM production. The largest growth categories of natural gas types are shale gas and conventional natural gas from Alaska (the result of predicted pipeline construction completion). Shale gas is by far the largest growth category and by 2035 might be close to total conventional onshore volumes (U.S. DOE EIA, 2010e). Figure 3-4 presents EIA’s predictions for production of natural gas by type.



Source: U.S. DOE EIA, 2010f.

Figure 3-3. Projections of Natural Gas Consumption and Supply

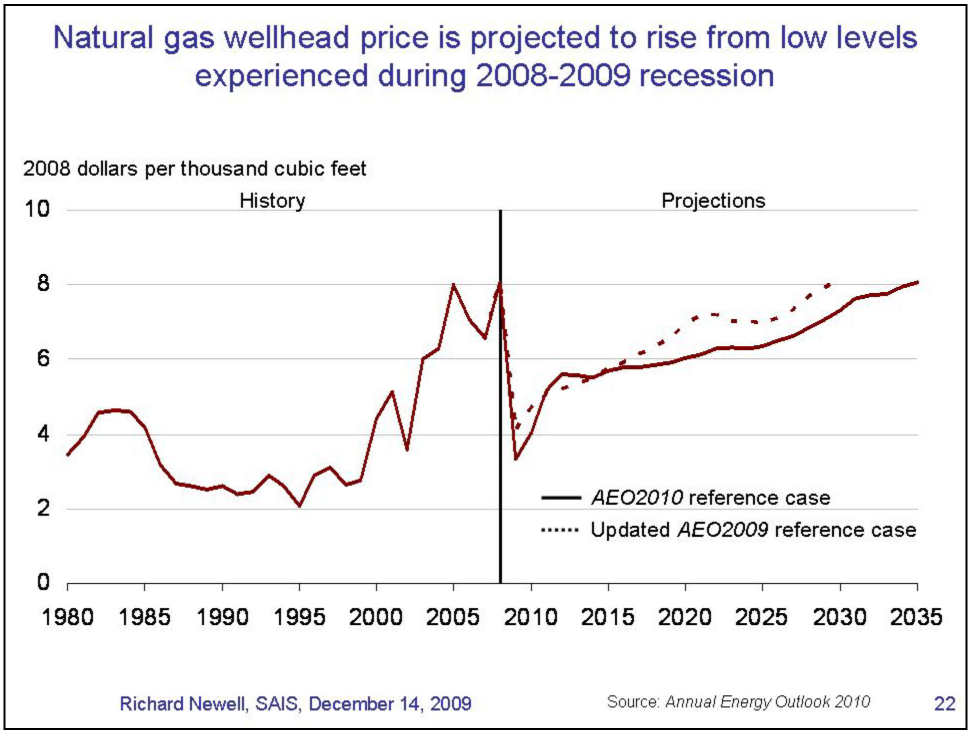


Source: U.S. DOE EIA, 2010f.

Figure 3-4. Projections of Shares of Total Gas Production by Type

3.6.2 Wellhead Gas Price Projections

Wellhead gas prices reached an historic peak in 2008, averaging $7.96/Mcf in the United States (for all gas, regardless of origin). In 2009, partly due to the recession, prices fell to the low point of the decade (averaging $3.71/Mcf). U.S. DOE EIA (2010e) predicts that wellhead prices will begin to recover in 2010, rising to about $5/Mcf in 2012 and about $5.50/Mcf in 2015. Prices will reach $6/Mcf in about 2020 (see Figure 3-5).



Source: U.S. DOE EIA, 2010e.

Figure 3-5. Projections of Natural Gas Wellhead Price

For 2010, through April, EIA shows a modest increase in the average monthly wellhead price each month on a year-over-year basis (U.S. DOE EIA, 2010e). Wellhead gas prices usually rise in the winter and decline in the summer following spikes and troughs in demand. Therefore, the average wellhead prices for the same month each year (e.g., January 2009 to January 2010) should be compared to accurately assess any trends. Table 3-21 shows the recent data on average U.S. wellhead price from 2008 to April 2010. As the table shows, prices in early 2010 are nearly unchanged at about 70 cents/Mcf higher than they were in the same month in 2009, but still substantially below the wellhead prices shown for 2008.

Basis differentials must be considered if projections of wellhead price are applied to individual projects in different parts of the United States. Basis differentials reflect the factors that make costs to individual projects different from the average U.S. wellhead prices shown in U.S. DOE data (e.g., transportation cost differences). Some of this differential can be seen in the differences between the U.S. average wellhead price and the wellhead prices by state shown in Table 3-12.

Table 3-21. Average Monthly U.S. Wellhead Price, 2008–2010

Month	2008	2009	2010	Difference 2008-2009	% Change 2008-2009	Difference 2009-2010	% Change 2009-2010
January	$7.16	$5.15	$5.14	($2.01)	-28.1%	($0.01)	-0.2%
February	$7.71	$4.19	$4.89	($3.52)	-45.7%	$0.70	16.7%
March	$8.44	$3.72	$4.36	($4.72)	-55.9%	$0.64	17.2%
April	$9.04	$3.43	$3.92	($5.61)	-62.1%	$0.49	14.3%
May	$10.15	$3.45		($6.70)	-66.0%		
June	$10.79	$3.45		($7.34)	-68.0%		
July	$11.32	$3.43		($7.89)	-69.7%		
August	$8.34	$3.14		($5.20)	-62.4%		
September	$6.72	$2.92		($3.80)	-56.5%		
October	$5.50	$3.60		($1.90)	-34.5%		
November	$4.75	$3.64		($1.11)	-23.4%		
December	$5.52	$4.44		($1.08)	-19.6%		

Source: U.S. DOE EIA, 2010c.

3.6.3 Trends in Costs of Production

A number of trends could affect the costs of production, some long-term, some only short-term. Each of these types are discussed in the sections below.

3.6.3.1 Short-term Trends

Short-term trends include easing of supply constraints on materials and labor triggered by low gas prices (there are few demands for drilling rigs, pipe, and operating labor when gas prices are low), but this is offset by tight credit, such as that experienced in the recent recession. As prices recover, supply might go down, driving up prices; continuing tight credit could diminish this short-run price effect, however.

U.S. DOE EIA (2010e) discusses some trends in costs of CBM production over much of the last decade that provide some insight into potential short-term trends. According to this source, costs of production (as defined in Section 3.5.2.2), including lease equipment and O&M costs, have risen steadily. However, these costs fell in 2009 as the plunge in gas prices reduced demand for lease equipment. Operating costs were also reduced in most areas due to reduced fuel costs; well-servicing costs also generally fell. The only exception to the reduction in operating costs was the rising cost of electricity in the Powder River and the Appalachian Basins, which increased operating costs in these basins in 2009. In the four basins (Appalachian, Black Warrior, Powder River, and San Juan Basins) studied by U.S. DOE EIA (2010f), O&M costs rose overall an average of 8 percent in 2008 and fell by 1 percent in 2009. Equipment costs rose 16 percent and fell 10 percent in 2009.

As seen in the last two years, costs of production tend to rise and fall as gas prices rise and fall. This relationship between costs and gas price can also be seen in Figure 3-6, which shows the longer-term relationship between cost and price for conventional gas production (the same general principal should hold true for CBM). As the figure shows, in years with low gas prices, costs tend to be lower, and in years with high prices, costs tend to be higher. Thus, assuming that credit eases, and given that prices are expected to rise modestly over the next few years, EPA expects that costs of production might also tend to rise modestly over the short run.

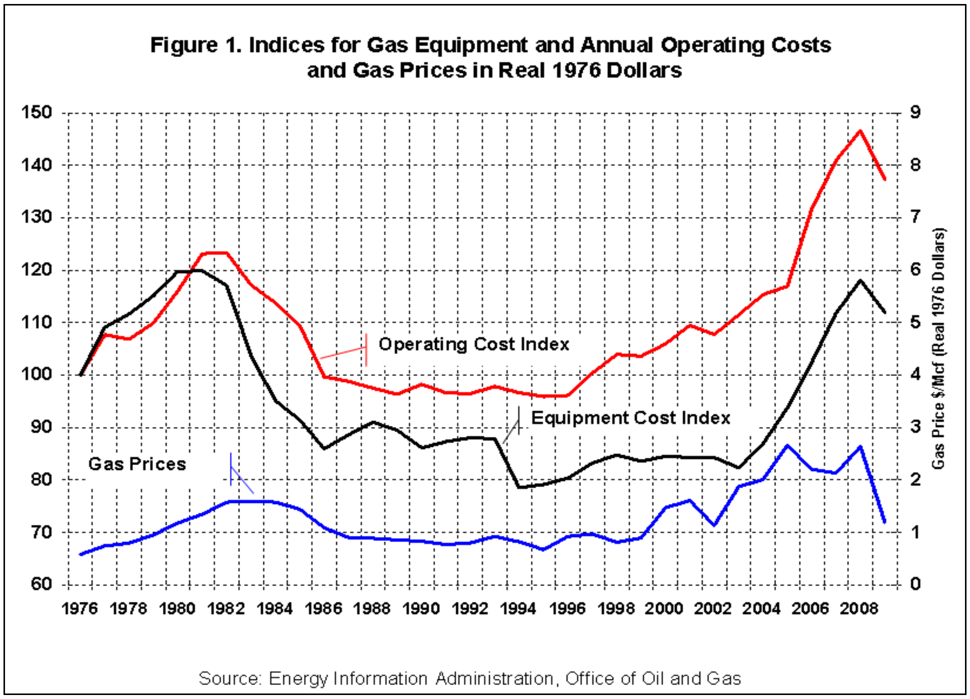


Figure 3-6. Indices for Gas Equipment and Annual Operating Costs and Gas Prices in Real 1976 Dollars

3.6.3.2 Long-term Trends

Key long-term factors affecting costs of production include availability of pipelines to transport CBM to central distribution hubs, the number of years over which development has occurred in a region, technology changes, and project-specific trends such as potential decreases in produced water production over time.

The most important factors for analyzing long-term effects of increased costs of production due to potential new regulatory requirements are the long-term trends. These long-term trends, however, tend to move costs in opposite directions. Increased access to pipeline transportation tends to lower costs of transportation, as demand for pipeline capacity no longer outstrips its supply. This contributes to a lower basis differential and thereby a higher wellhead price by which to offset costs.

Years of development in a basin also can affect long-term production costs. As easy-to-reach coalbeds are tapped, future development relies on producing from deeper coalbeds, thinner coalbeds (e.g., those that are only a few feet thick), “tighter” coalbeds (those with fewer spaces that allow gas to escape easily), or coalbeds with lower-rank coals (with less gas), all of which can be more expensive to produce and/or generate lower revenues. Deeper coalbeds require deeper wells, taking longer to drill and requiring more piping and often more energy to bring the gas to the surface. Tighter coalbeds might require special treatment before they are produced (hydrofracturing—a method of opening up additional cracks in the coal seam to allow gas to escape more readily—is an additional expense if tighter coalbeds are to be produced economically [U.S. EPA, 2004b]).

Also affecting long-term trends in costs are changes in technologies in producing CBM (e.g., multiseam completions and horizontal drilling), although these changes can have an uncertain effect on long-term cost trends. These technology changes can increase total costs, but reduce costs per Mcf of gas produced. Multiseam completions allow several coalbeds at varying depth to be produced at the same time (U.S. DOE, 2003) or can be used to add CBM to a conventional oil and gas project when the well passes through a coal seam. Horizontal wells can be drilled laterally through a coalbed, increasing the length of well in contact with the coalbed (E&P, 2007). This latter method can allow thin coalbeds, once dismissed as uneconomical, to be produced. Both of these technologies can be used to produce more gas from one well, potentially lowering the cost per Mcf to produce the gas.

3.6.4 The Future of Existing Basins

EPA investigated the potential for CBM production in the key discharging basins to consider the potential for new projects and continued long-term production from existing projects. Table 3-22 summarizes estimates of the technically recoverable resources within each of the major discharging basins (except Green River) and presents information on recent well drilling and production trends and expected future trends. Additionally, it summarizes an assessment of how accessible the remaining resources are and how accessible the gas is to key market hubs (ARI, 2010b).

In general, the PRB is the discharging basin with the most resource potential, even under conservative estimates. Adding major pipeline capacity (especially the recent 1.8 Bcf/day addition) has increased the access of PRB CBM to major markets, increasing the potential for production. The Appalachian and Raton Basins also show increases in drilling and production trends, but Black Warrior/Cahaba, the basin with some of the oldest CBM development, might be at or close to a peak in drilling and production (ARI, 2010b).

Table 3-22. Summary of Information Important to Future Production Trends in the Major Discharging Basins

Basin	Resource Potential	Well Drilling	Production	Resource Access	Market Access
PRB	~14-52 Tcf might be technically recovered, mostly in the Big George coal horizon in Wyoming.	After reaching a peak of over 3,500 wells drilled in 2001, drilling has remained at 2,000–2,500 wells/year for the past six years.	Rapid increase 1997–2000 with slower growth 2001–2006 as produced water issues limited new drilling. As drilling resumed, production increased again.	43% of CBM resource underlies federal lands; 6% of the CBM resource in PRB is off limits to all development; 21% is subject to federal leasing restrictions that limit development during certain months.	In 2000, Cheyenne Hub began gas transport but access to markets was limited by lack of capacity and unfavorable basis differentials. Addition of Rockies Express Pipeline has added substantial capacity.

Table 3-22. Summary of Information Important to Future Production Trends in the Major Discharging Basins

Basin	Resource Potential	Well Drilling	Production	Resource Access	Market Access
Appala-chian	~8.4–9.3 Tcf might be technically recoverable from West Dunkard and Pocahontas formations.	Drilling was steady 1997 to 2003, rising in 2004 and peaking in 2006, but expected to remain high.	Rising since 2003, and should continue. Activity mostly in Central Appalachian Basin.	2% underlies federal lands; 1% is inaccessible and 1% is accessible with restrictions on drilling. A small portion of the resource underlies state government lands.	Favorably located near major pipelines to northeastern markets; near Dominion South Point Hub. Usually a negligible or slightly positive basis differential.
Black Warrior/ Cahaba	~5.1–7.0+ Tcf might be technically recoverable.	Drilling increased steadily 1997–2006, then declined. Expected to remain relatively high.	Remained steady from 1997–2006. May not be sustainable in the future.	4% classified federal lands, 2% inaccessible to leasing. Small portion underlies state government lands.	Favorably located near major pipelines transporting gas from Gulf Coast to northeastern markets.
Raton	~1.59–8.2 Tcf might be technically recoverable.	Drilling increased steadily 1998–2007, after which it has declined.	Steady increase 1998–2007; peak should be maintained for foreseeable future.	Much CBM resource underlies federal lands, some inaccessible, some accessible under development restrictions.	Pipeline expanded in 2005 from the Raton Basin into Oklahoma panhandle, and then again in 2008 from Las Animas County area to the Cheyenne Hub.

Source: ARI, 2010b.

4. ENVIRONMENTAL ASSESSMENT CONSIDERATIONS

CBM produced water is released to the environment when it is discharged directly to surface waters, managed using land application or irrigation, or stored in impoundments or constructed wetlands. The following sections describe the documented and potential environmental impacts associated with the discharge of CBM produced water and zero discharge with beneficial use management options.

EPA conducted a broad, nationwide literature review of environmental impacts from CBM produced water discharges to identify the impacts discussed in this chapter. EPA identified and reviewed documents from the following information sources:

- Peer-reviewed literature;
- State and federal agency reports;
- CBM site visit reports;
- CBM stakeholder meeting notes;
- CBM permits;
- Nongovernmental organization (NGO) reports;
- Industry publications;
- News organization publications; and
- University research.

In total, EPA identified over 1,000 documents and performed a detailed review of 452 of these. EPA selected publicly available peer-reviewed literature as well as state, federal, university, and news/industry/NGO articles that were publicly available. Table 4-1 summarizes the results of literature review by search category and type of environmental impact.

Table 4-1. Summary of Literature Review Results by Search Category and Type of Environmental Impact

Information Source	Number of Documents Identified	Number of Documents Examined in Detail	Number of Unique Documents That Discussed Environmental Impacts	Number of Documents by Impact Type [a]			
				Documented	Potential	Nonsurface Water	No Impact
Peer-Reviewed Literature	46	19	6	1	3	4	1
State and Federal Agency Reports	467	116	38	1	25	24	8
CBM Site Visit Reports	22	22	5	0	2	2	3
CBM Stakeholder Meeting Notes	41	41	5	0	3	1	3

Table 4-1. Summary of Literature Review Results by Search Category and Type of Environmental Impact

Information Source	Number of Documents Identified	Number of Documents Examined in Detail	Number of Unique Documents That Discussed Environmental Impacts	Number of Documents by Impact Type [a]			
				Documented	Potential	Nonsurface Water	No Impact
NGO, News and Industry Publications	428	195	47	2	26	34	2
University Research	74	57	23	2	15	18	0
Total	**1,078**	**451**	**124**	**6**	**74**	**83**	**17**

a – Note that a document may discuss more than one impact type. Therefore, the sum of the number of documents by impact type may exceed the number of unique documents identified for a given information source.

4.1 Documented Impacts From the Direct Discharge of CBM Produced Water

EPA defines a documented environmental impact as an impact to stream water quality, morphology, or aquatic community that resulted from or was contributed to by the direct discharge of CBM produced water to a receiving stream. EPA's literature review identified only a limited number of scientific studies documenting the environmental impacts of CBM produced water discharges on aquatic ecosystems (see Table 4-2). Several authors in the research field acknowledge that few studies have been conducted to specifically address the effects of CBM produced water on receiving streams (Davis et al., 2006; MacDonald, 2007; Wang et al., 2007). All of the identified studies concerned the PRB in Wyoming and Montana and the Black Warrior Basin in Alabama.

Some of the documented impacts focused on changes to fish species population diversity due to CBM produced water discharges. Two related papers, Davis et al., 2006, and Davis, 2008, investigated the impact of CBM discharges on fish assemblages in the PRB. Based on her review of relevant research and her own research, Davis found conflicting results regarding the impacts of CBM produced waters on fish. In her master's thesis, Davis observed that CBM produced waters had some impact on fish assemblages (Davis, 2008). Specifically, she found decreased abundance of certain fish in streams with elevated bicarbonate. She also found decreasing biotic integrity[18] in streams with increasing conductivity. (Increased conductivity and bicarbonate are characteristics of some CBM produced waters.) However, the same study found that species richness and biotic integrity were similar between sites with and without CBM discharges nearby. Davis also observed a weak relationship or none at all between overall index of biotic integrity scores and the number or density of CBM wells in a drainage area (Davis, 2008). These findings suggest that while CBM discharges overall had little effect on the fish present in the

[18] Biotic integrity is the capability to support and maintain a balanced, integrated, adaptive community of organisms having a species composition, diversity, and functional organization comparable to that of the natural habitat of the region (Karr, 1981).

receiving streams, elevated bicarbonate or conductivity—which are on average higher in streams that receive CBM produced water—may negatively affect fish assemblages over time.

Table 4-2. Summary of Documented Impacts From the Direct Discharge of CBM Produced Water Cited in Peer-Reviewed Literature

Citation	Impact Type	Summary
O'Neil et al., 1991a (cited in Davis et al. 2006)	Changes in communities of aquatic organisms	O'Neil et al. observed changes in fish species abundance and reproduction in response to water quality alterations resulting from CBM produced water discharges in the Black Warrior Basin. This suggests that CBM discharges are altering the aquatic environment and may cause permanent changes in species assemblages.
Davis, 2008	Changes in communities of aquatic organisms	In Davis's comparison of streams in the PRB with and without CBM development, some results indicated that CBM discharges were impacting fish assemblages, while others showed no impact. Impacts tied to CBM produced water discharges included a correlation of increased conductivity with decreased biotic integrity, a correlation between decreased abundance of certain fish with an increase in bicarbonate, and the presence of the salt-tolerant northern plains killifish only in streams receiving CBM produced water discharges.
Confluence Consulting, 2004b (cited in Confluence Consulting, 2004a)	Changes in aquatic organisms and riparian plant communities	In a study of the effects of CBM development on fish and water quality, Confluence Consulting observed elevated levels of dissolved solids, reduced numbers of sturgeon chub in the Powder River, and a prevalence of salt-tolerant shrubs.
Vickers, 1990	Changes in communities of aquatic organisms	In a study determining the effects of CBM produced water on surface waters of the Black Warrior Basin in Alabama, researchers from the University of Alabama observed a decrease of total macroinvertebrates as the in-stream chloride concentration at Shoal Creek increased. The decrease in taxa was not completely dependent upon chloride concentration, but may have been influenced by in-stream components and subsequent mixtures.
Mount et al., 1992	Changes in communities of aquatic organisms	In an in-stream study of surface waters in the Cedar Cove degasification field, the Geological Survey of Alabama (GSA) found no significant effects in streams on native invertebrates (acute toxicity of *Ceriodaphnia*) at chloride concentrations of 519 mg/L and below and consistent effects at chloride concentrations of 615 mg/L and above.
O'Neil et al., 1993	Changes in communities of aquatic organisms	A GSA study found that environmental effects caused by CBM water discharges were related to TDS rather than metals or other constituents. This study concluded that elevated chloride levels in CBM produced waters from coal seams in Alabama were the main driver behind deleterious effects on stream conditions. Specifically, an in-stream limiting chloride concentration of < 565 mg/L had no significant effect on the community structure of benthic macroinvertebrates. In contrast, chloride concentrations of > 565 mg/L in produced water always degraded or impaired the benthic macroinvertebrate community.

In a related review paper, Davis et al., 2006, cited a number of studies performed in the Black Warrior Basin in Alabama, where fish species diversity and biomass remained unchanged following the discharge of CBM produced water (O'Neil et al., 1989, cited in Davis et al., 2006; O'Neil et al., 1991a, cited in Davis et al., 2006; Shepard et al., 1993, cited in Davis et al., 2006). However, O'Neil et al., 1991a (cited in Davis et al., 2006) observed water quality alterations from CBM discharges, resulting in changes in fish species abundance and reproduction that could cause permanent impacts to communities.

These examples from Davis highlight both the limited number of scientific studies that have investigated the environmental impacts of CBM produced waters and their conflicting results. Overall, the data suggest that environmental impacts from CBM produced water discharges are likely to be site-specific and dependent upon the water quality of the produced water, type of species present, and the metrics used to evaluate the impacts on aquatic organisms.

Confluence Consulting, 2004b (cited in Confluence Consulting, 2004a) describes a study of the effects of CBM development on fish and water quality. Sampled sites along the Powder River with CBM discharges contained elevated dissolved solids concentrations compared to baseline conditions for the Powder River (USGS, 2006a). Sampling results also showed a rarity of sturgeon chub, a species of special concern, and encroachment of tamarisk, a salt-tolerant, introduced shrub that could outcompete the more desirable cottonwoods.

The remaining documented impacts focused on problems with the salinity of CBM produced water and its impact on aquatic vegetation and macroinvertebrate communities. The Geological Survey of Alabama (GSA) completed a study in 1993, which documented CBM produced water data collected during the late 1980s (O'Neil et al., 1993). The study tested numerous water quality parameters including dissolved oxygen, five-day biochemical oxygen demand ($BOD_{5)}$, TDS, turbidity, bicarbonate, carbonate, alkalinity, silica, metals (e.g., arsenic, barium, cadmium, chromium, cobalt, iron, lead, manganese, mercury, selenium, silver, strontium, zinc), calcium, magnesium, sodium, potassium, sulfate, chloride, fluoride, nitrate, ammonia, and orthophosphate. Dr. Pat O'Neil, GSA, stated that the study found that environmental effects caused by CBM water discharge were related to TDS rather than metals or other constituents (U.S. EPA, 2007). Specifically, this study concluded that elevated chloride levels (above 565 mg/L) in CBM produced waters were the main cause of harmful effects on stream conditions. Dr. O'Neil noted that only small streams were included in this study, and postulated that any CBM produced water discharges into large rivers would be diluted, which may dampen any deleterious effects (U.S. EPA, 2007).

Vickers (1990) describes a study conducted at an Amoco project area by the University of Alabama, Department of Mineral Engineering and Department of Biology, in 1989. The study found that, as the in-stream chloride concentration at Shoal Creek increased, total macroinvertebrate taxa decreased. However, this was not found at the Fox Creek Test Site. Taxonomic richness (total species) was not affected by chloride in-stream concentrations at either site. Moreover, the study found that the decrease in total taxa did not completely depend upon chloride concentration, but may have been influenced by in-stream components and subsequent mixtures. Mount et al. (1992) describes an in-stream study of surface waters in the Cedar Cove degasification field conducted by the GSA from 1986 to 1988. Study results found no significant effects on native invertebrates in streams (acute toxicity of *Ceriodaphnia*) at chloride concentrations of 519 mg/L and below, and consistent effects at concentrations of 615 mg/L chloride and above.

One of the limitations of studies conducted in CBM production basins is a lack of baseline conditions of streams established prior to CBM development and the discharge of produced water. Without adequate baseline information, the degrees of aquatic impacts are difficult to ascertain, especially given the seasonal variability of rainfall and consequent stream flow fluctuations (particularly in arid regions such as the PRB) and the natural occurrence of many contaminants of concern in produced water (e.g., chlorides and sodium) (Davis, 2008).

4.2 Potential Environmental Impacts From the Direct Discharge of CBM Produced Water

EPA defines a potential environmental impact as an impact to stream water quality, morphology, or aquatic community that could potentially result from or be contributed to by the direct discharge of CBM produced water to a receiving stream. EPA's literature review identified 74 scientific studies, reports, and other sources describing potential environmental impacts from CBM produced discharges. The primary potential impacts include those to vegetation, water quality, and organisms due to changes in stream volume, turbidity, salinity, sodicity, SAR, TDS, specific conductance, toxicity, temperature, and pH. Some of these potential impacts are based on knowledge or observations of unrelated discharges with similar pollutant levels and the impacts from those pollutants.

A number of sources expressed concern over the potential for changes in stream water volume caused by CBM discharges to alter aquatic habitats. A higher receiving water volume can increase suspended sediment and streambed erosion, which can affect the aquatic organisms that inhabit these waters (Arthur, 2001; ALL, 2003; Arthur et al., 2001). Erosion can destroy vegetation within streams (ALL, 2003; Fisher, 2001; Regele and Stark, 2000), impacting aquatic biota that have particular flow requirements for food, habitat, and reproduction (Rawn-Schatzinger et al., 2004; Davis et al., 2006; Regele and Stark, 2000). Flow volume changes from CBM discharges can also increase turbidity, which might help invasive species outcompete native species under the new flow conditions (Davis et al., 2006; Bonner and Wilde, 2002, cited in Davis et al., 2006; Gradall and Swenson, 1982, cited in Davis et al., 2006).

Another concern expressed in the literature is the potential for CBM discharges to alter salinity levels in receiving streams (also discussed with documented impacts in Section 4.1). Rawn-Schatzinger et al. (2004) suggest that salinity, along with sodicity and toxicity, are the biggest issues with CBM produced water discharges. Saline discharges from CBM produced waters can alter plant communities as native species are replaced with salt-tolerant species (Keith et al., 2003). However, not all locations are impacted equally by such water quality changes. For example, Stanford and Hauer (2003) noted that because the Tongue River is more dilute than the Powder River, CBM discharges with high salinity concentrations are more likely to cause detrimental effects on the Tongue River than the Powder River. Conversely, CBM produced water discharges can also impact aquatic species by diluting receiving waters with large volumes of less saline CBM produced water, thus altering the habitat for aquatic species that are acclimated to more saline waters (Clearwater et al., 2002, cited in MacDonald, 2007).

An elevated SAR value in CBM discharges can also affect aquatic systems (Confluence Consulting, 2004a; Osborne and Adams, 2005). Other components in CBM produced waters that are toxic to native plants and animals at elevated concentrations include ammonia, hydrogen sulfide, bicarbonate, selenium, TDS, chloride, and boron (Fisher, 2001; MacDonald, 2007; Rice et al., 2000, cited in Davis et al., 2006; ALL, 2003). Depending on species tolerance, impacts to aquatic organisms can vary greatly with some species able to acclimate to the new environment more quickly than others (Davis, 2008; MacDonald, 2007).

Several studies identified toxicity concerns from CBM produced water constituents ranging from sodium bicarbonate to pH to metals. Elevated concentrations of and exposure time to sodium bicarbonate, (a major constituent of CBM produced water in the Tongue and Powder River drainage basins) decreased fathead minnow survival, increased incidence of lesions and kidney damage, and may impact freshwater ecosystems by interfering with ion uptake by fish (USGS, 2006b). Increased water-quality variation from CBM discharges to a receiving stream, particularly with regard to pH, could potentially cause physiological stress to aquatic organisms (O'Neil et al., 1991b). In addition, streams receiving produced water tend to have increased concentrations of metals such as selenium, chromium, cadmium, copper, aluminum, and iron. Elevated selenium concentrations can potentially bioaccumulate in fish and migratory aquatic birds, causing effects such as low reproduction, increased mortality, and embryonic deformities (Ramirez, 2005, citing Ohlendorf et al., 1988). In PRB receiving wetlands, the U.S. Fish and Wildlife Service (U.S. FWS) measured cadmium and chromium concentrations that exceed the thresholds considered hazardous to aquatic life (U.S. DOI, 2005). The same study found iron, manganese, lead, and copper in CBM produced water discharges that were above concentrations that would impact fish and birds (U.S. DOI, 2005).

A joint study by the Montana Department of Environmental Quality, Montana Fish and Wildlife, and EPA Region 8 estimated future water quality for streams receiving CBM produced water discharges in the PRB (Horpestad et al., 2001). To perform their analysis, the researchers estimated the potential number of new wells in PRB over a 20-year period and used historical data to estimate typical flow, discharge, conveyance loss, electric conductivity (EC), and SAR values for surface waters. The modeling results from the analysis suggest that CBM produced water discharges will significantly alter water quality in five of the seven rivers in the PRB over a 20-year period. The study concluded that the impacted rivers would likely be rendered unsuitable for irrigation based on predicted ratios of EC and SAR values in the receiving water, which exceed the threshold levels for no reduction in infiltration (Horpestad et al., 2001).

Table 4-3. Scientific Studies Evaluating Potential Environmental Concerns From the Direct Discharge of CBM Produced Water

Citation	Impact Type	Summary
Clearwater et al., 2002 (cited in MacDonald., 2007)	Changes in water quality and aquatic communities	Changes in volume and salinity of water in receiving streams in the PRB can impact resident biota by disrupting environmental cues, which can alter reproduction and normal species behavior.
Patz et al., 2004 (cited in Davis et al., 2006)	Changes in water quality	The pH of CBM produced water may fluctuate due to atmospheric exposure following discharge to a receiving water in the PRB. These changes in pH can make downstream impacts difficult to pinpoint.
Horpestad, 2001 (cited in Todd, 2006)	Changes in water quality	In areas with minimal precipitation, such as eastern Montana, salts from CBM produced water can accumulate in surface waters.
Klarich et al., 1980 (cited in Regele and Stark, 2000)	Changes in water quality	Raising the salinity of southeastern Montana waters above 1,200 micromhos will potentially affect the biological health in streams receiving produced waters.

Table 4-3. Scientific Studies Evaluating Potential Environmental Concerns From the Direct Discharge of CBM Produced Water

Citation	Impact Type	Summary
Forbes et al., 2002, and Forbes et al., 2001 (cited in MacDonald et al., 2007)	Changes in water quality and aquatic communities	The water quality of CBM produced water and PRB receiving waters were linked to acute and chronic toxicity effects in *Ceriodaphnia dubia*, *Daphnia magna*, and fathead minnows.
Skaar et al., 2004 (cited in Davis et al., 2006)	Changes in water quality and aquatic communities	Exposure to sodium bicarbonate in reconstituted Tongue and Powder River water resulted in chronic and acute toxicity and mortality in fathead minnows.
Skaar et al., 2005	Changes in water quality and aquatic communities	Chronic exposure to sodium bicarbonate from simulated Tongue and Powder River water resulted in gill lesions, gill necrosis, and kidney damage in fathead minnows.
Ramirez, 2005	Changes in water quality, aquatic communities, and migratory bird communities	The U.S. FWS (citing Ohlendorf et al., 1988) reported that streams receiving produced water tend to have increased selenium concentrations, which can impact fish and migratory aquatic birds due to bioaccumulation. Birds with increased selenium concentrations can have low reproduction, increased mortality, and embryonic deformities. In addition, any prior impoundment of the produced water before discharge to receiving waters can increase selenium concentrations even further due to evaporation.
Ramirez, 2005	Changes in water quality and aquatic communities	U.S. FWS (citing Eisler, 2000) found that cadmium concentrations in aquatic invertebrates from some CBM produced water receiving sites exceeded the 0.1 µg/g “view with caution” level. Chromium in tiger salamanders at a number of sites ranged from 18.6 to 137 µg/g, and chromium in fathead minnows ranged from 24.4 to 307 µg/g. (Chromium concentrations of 4 µg/g or greater are considered evidence of chromium contamination.)
USGS, 2006b	Changes in water quality and aquatic communities	In a laboratory study, the USGS found that increased concentrations of, and exposure time to, sodium bicarbonate, a major constituent of CBM produced water in the Tongue and Powder River drainage basins, decreased fathead minnow survival, increased incidence of lesions and kidney damage, and interfered with ion uptake by fish.
USDOI, 2005	Changes in water quality and aquatic communities	The U.S. FWS measured cadmium concentrations ranging from 6.7 to 9.3 µg/L in wetlands in the PRB that receive CBM produced waters, exceeding the threshold of 3 µg/L considered hazardous to aquatic life. Chromium concentrations were typically low, except for one wetland site where concentrations in fathead minnows ranged from 24.4 µg/g to 307 µg/g, greatly exceeding the 4 µg/g threshold considered hazardous.
USDOI, 2005	Changes in water quality, aquatic communities, and bird communities	In a PRB study by U.S. FWS that took place from 2000 to 2002, concentrations of iron, manganese, lead, and copper in CBM produced water discharges were above concentrations that would impact fish and birds.
Jackson and Reddy, 2007	Changes in water quality and aquatic communities	Most CBM produced water being discharged at outfalls into the PRB was considered unsuitable for aquatic life due to aluminum and copper concentrations greater than the water quality standards for aquatic life.

Table 4-3. Scientific Studies Evaluating Potential Environmental Concerns From the Direct Discharge of CBM Produced Water

Citation	Impact Type	Summary
Mount et al., 1992	Changes in water quality	The results of a study funded by the Gas Research Institute at the Cedar Cove degasification field indicated that laboratory toxicity tests could be used to predict in-stream effects of CBM produced water. The study reported that the TDS concentration, specifically the chloride concentration, accounted for most of the toxicity associated with CBM produced water at the site.
O'Neil et al., 199b	Changes in aquatic communities	CBM produced water discharges may account for some observed changes in fish abundance in the receiving waters of the Cedar Cove degasification field; however, the changes were within the range of variation observed under natural conditions.
Gore, 2002	Changes in water quality, aquatic communities, and morphology	A study by Columbus State University used model simulations to evaluate the impact of increased flows from CBM produced water on aquatic communities. The modeling results determined that all study locations would lose habitat, impacting and possibly destroying macroinvertebrates and western silvery minnows and destabilizing the river ecosystem. Small increases in flow over a long period of time flushed organisms, decreased organic matter, changed channel morphology, and increased sedimentation, which could cause declines in the macroinvertebrate community, decreasing fish populations and decreasing diversity in the ecosystem.

4.3 Nonsurface Water Environmental Impacts Associated With CBM Produced Water

EPA defines a nonsurface water environmental impact as an impact caused by CBM produced water that did not result from the direct discharge of produced water to a receiving stream. Nonsurface water environmental concerns discussed in the literature can be divided into two broad categories: (1) environmental impacts caused by the land application (e.g., irrigation or dust control) of CBM produced water and (2) environmental impacts that resulted from impounded CBM produced water (e.g., impoundment control technologies, livestock watering impoundments, and constructed wetlands).

Nonsurface water impacts were the predominant type of environmental impact described in the literature (see Table 4-1). EPA did not distinguish between documented and potential nonsurface water impacts. The most prevalent issues cited were groundwater issues, such as groundwater contamination resulting from both CBM produced water land application and impoundments, but irrigation and soil toxicity impacts were also frequently discussed.

4.3.1 Land Application Impacts

The land application of CBM produced water for activities such as irrigation and dust control can cause pollutants in CBM produced water to infiltrate into local groundwater systems. Pollutants that can infiltrate into groundwater include heavy metals, salts, ions, and organic material often present in CBM produced water (ALL, 2006b; Fisher, 2001), which can contaminate drinking water supplies (Veil et al., 2004).

Elevated SAR and salinity in CBM produced water applied to land can alter the soil structure of fine-textured soils by causing swelling and dispersion, which decreases pore size and reduces water infiltration rates (USGS, 2006a; ALL, 2002; ALL, 2003). Reduced soil porosity increases runoff of rain and irrigation waters, which can decrease the ability of soils to support plant life (Arthur, 2001; USGS, 2006a). CBM produced waters with elevated salinity can also decrease air and water permeability in soil. Fine clayey soils, of which the PRB is primarily composed, are particularly prone to impacts from the saline and high SAR content of CBM produced water discharges (USGS, 2006a; ALL, 2002).

Even in nonsensitive soils, the increased salinity of CBM discharges can be toxic to plants and decrease crop yield (Veil et al., 2004; Regele and Stark, 2000). If soil water is too saline, plants must exert more energy to extract waters from soils, decreasing productivity (ALL, 2003), which can cause plant communities to shift to more salt-tolerant species, decreasing diversity and altering the ecosystem (Arthur et al., 2001). In one paper, Stanford and Hauer (2003) observed areas in Montana where land irrigated with CBM produced water contained very little or no vegetation. In areas with abundant rainfall, salts from CBM produced water can leach from the soil; however, in more arid regions (e.g., Montana), salts can accumulate with each application of CBM water (Veil et al., 2004) and render the soil unfit to support vegetation.

In addition to the articles discussed above, EPA identified several published scientific studies investigating the potential nonsurface water impacts from land application of CBM produced water (see Table 4-4). These studies primarily focus on groundwater and soil impacts due to CBM activities.

Table 4-4. Scientific Studies Evaluating Nonsurface Water Environmental Concerns Associated With Land Application of CBM Produced Water

Citation	Impact Type	Summary
Buchanan, 2005	Soil	High concentrations of salts and sodium in CBM produced waters pose a potential risk to soil structure and porosity when used for irrigation. Finer, more clayey soils exhibited a more significant change in hydraulic properties when irrigated with CBM produced water than coarser soils. Irrigation using CBM produced water with high sodium concentrations increased runoff volumes and decreased infiltration rates.
Ganjegunte et al., 2005	Soil	Irrigation with CBM water can significantly impact certain soil properties, such as infiltration and conductivity.
Rice et al., 2002 (cited in Kirkpatrick, 2005)	Soil	CBM waters in the northwest PRB had high SAR and TDS concentrations. Surface discharge of this water could change soil permeability.
Robinson, 2002 (cited in Kirkpatrick, 2005)	Soil	Repeated wetting and drying cycles from applying CBM produced water can result in greater SAR levels in soils due to concentration of ions from evaporating water. The increase in soil SAR values can alter soil properties (e.g., soil pore size) and decrease the infiltration of water over time.
Todd, 2006	Soil	Irrigation with CBM water can have long-term impacts on soil and plant productivity. Experimental irrigation with CBM produced waters decreased forage yield, height, and nitrate concentrations of crops.

Table 4-4. Scientific Studies Evaluating Nonsurface Water Environmental Concerns Associated With Land Application of CBM Produced Water

Citation	Impact Type	Summary
McBeth et al., 2003	Soil	Study results suggest that in arid and semiarid regions, land disposal of CBM produced waters may cause precipitation of calcium carbonate in soils, which can decrease infiltration rates and increase runoff and erosion rates.
Robinson et al., no date	Soil	A study published by Montana State University and funded by several conservation districts in the state concluded that CBM produced water used for irrigation purposes can negatively affect soils. EC, SAR, and exchangeable sodium percentage (ESP) values were significantly elevated, with approximately 50% of the resultant values exceeding the reported thresholds for salt injury to crops (i.e., alfalfa, corn, and specialty crops) commonly grown in the area and the thresholds for soil dispersion.
Ramirez, 2005	Soil	The U.S. FWS report on CBM produced water contaminants contends that irrigation with high-saline produced waters causes salt to accumulate, which destroys soil structure and inhibits plant uptake of water. The SAR of produced water is typically 10 to 12 times the level for soil to support plants.
Ramirez, 2005	Bioaccumulation	In an assessment of CBM contaminants, the U.S. FWS reported that the land application of CBM produced water with elevated levels of selenium on marine Cretaceous shales (found in the eastern and western boundaries of the PRB) can mobilize selenium present in the shale. Selenium can bioaccumulate in the food chain up to 2,000 times the level present in water. Bioaccumulation is most likely to occur in areas with selenium sources, high evaporation rates, and closed containment reservoirs.
Ramirez, 2005	Groundwater	The U.S. FWS reported that infiltration of CBM produced water can rapidly contaminate groundwater by leaching salts and trace elements from the ground in addition to the water's original elevated salt and trace element concentrations.

4.3.2 Impoundment Control Technology Impacts

Surface impoundment impacts include groundwater impacts due to infiltration, the concentration or bioaccumulation of pollutants (e.g., salts, heavy metals) due to evaporation, and the potential creation of new aquatic habitats resulting in the introduction or proliferation of species in the area (e.g., West Nile Virus vector mosquitoes). In addition to the initial contamination, evaporation from impoundments can further concentrate pollutants in CBM produced water, decreasing the quality of water released to the environment through infiltration or discharge (ALL, 2002). If connected to surface water bodies, impoundment discharges can also degrade water quality in receiving waters (Roulson, 2007; ALL, 2003).

Impoundments can also create new habitats in CBM production areas (Doherty, 2007), which can introduce new species or cause the proliferation of species already in the area (Davis et al., 2006; Doherty, 2007). The proliferation of species such as West Nile virus vector mosquitoes due to CBM discharge ponds can cause human and wildlife health risks (Doherty, 2007).

As in impoundments, the salt concentrations in constructed wetlands can increase due to evaporation, which can impact soils and wetland plant survival (Kirkpatrick, 2005). Elevated salt concentrations can prevent the vegetation growth on the land once the CBM well is depleted, as the elevated salinity would prevent all but salt-tolerant plants from reestablishing (Kirkpatrick, 2005).

Table 4-5 lists several published scientific studies identified by EPA that investigate the potential nonsurface water impacts from control technologies for CBM produced water.

Table 4-5. Scientific Studies Evaluating Nonsurface Water Environmental Concerns Associated With Control Technologies for CBM Produced Water

Citation	Impact Type	Summary
ALL, 2007	Impoundments, Groundwater	In a study funded by U.S. DOE's Office of Fossil Energy (Tulsa) and the Montana Board of Oil and Gas Conservation, ALL used subsurface hydrogeologic data to investigate the effects of CBM impoundments on shallow groundwater. In the study, ALL observed a chemical shift in salt ions present in downgradient bedrock samples over background water quality.
Jackson and Reddy, 2007	Impoundments	Researchers from the Department of Renewable Resources at the University of Wyoming determined that arsenic is soluble and mobile in semiarid alkaline watersheds with mineral oxides and hydroxides and increases in concentration in disposal ponds over time.
Zou et al., 2006 (cited in Doherty, 2007)	Impoundments, Constructed Wetlands	In a GIS analysis of potential mosquito larval habitats in the PRB, Zou et al. determined that CBM development increased the habitat available for West Nile virus vector mosquitoes by 75% from 1999 to 2004.
Kirkpatrick, 2005	Constructed Wetlands	Some native PRB plants are naturally salinity-tolerant. However, the elevated salinity and sodicity associated with constructed wetlands for CBM disposal might prevent even salt-tolerant native species from reclaiming the area.

4.4 Assertions of No Environmental Impact Caused by CBM Produced Water

EPA identified several articles and documents that included general statements that CBM produced water discharges were not likely to cause an environmental impact; however, these statements were not substantiated by rigorous scientific research. EPA also identified several studies that concluded if the appropriate controls are in place (e.g., certain management practices or prior soil investigation), there will likely be minimal or no impacts from CBM produced water discharges.

A number of state and federal documents included statements of no environmental impact resulting from CBM produced water discharges. The majority of these statements were from National Environmental Policy Act (NEPA) Final Environmental Impact Statements (FEIS) and Environmental Assessments (EA) documents from the Bureau of Land Management (BLM); the remaining no impact claims were from a series of reports written by the BLM on the impacts of coal activities in the PRB, referred to as the PRB Coal Review. The NEPA documents usually prefaced statements of no environmental impact with some acknowledgment of the potential for CBM discharges to cause environmental harm; however, these potential impacts were not considered serious enough to stop the development of the CBM project and the overall operations were deemed not to cause any environmental impacts of concern (BLM, 2001, 2003a, 2003b, 2003c, 2004, 2005a). The PRB Coal Report discusses potential environmental impacts, but also discusses studies by the BLM demonstrating that CBM produced waters have not impacted the environment. For example, one BLM study concluded that, in Antelope Creek, Little Powder, Upper Belle Fourche, and Upper Cheyenne subwatersheds, CBM discharges would have minimal effect on permanent streams (BLM, 2005b). Another noted that as of 2002, CBM discharges to streams had not impacted surface waters farther than a few miles from the outfall, and discharges to unlined impoundments had no impact on groundwater or surface water farther than 25 feet away (BLM, 2006).

The GSA's long-term monitoring of fish and benthic communities in Little Hurricane Creek during controlled discharge of produced water has shown no effect on benthic invertebrate community structure at chloride concentrations below 600 mg/L. GSA believes this demonstrates that produced water can be discharged to a surface water without adverse effect if its potential toxicity is properly assessed and the discharge is managed and monitored accordingly (Mount et al., 1992).

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Appendix A

SUMMARY OF PERMITTING PRACTICES AND REQUIREMENTS

Alabama

The Alabama Department of Environmental Management (ADEM)'s Industrial/Mining Section began permitting CBM produced water discharges in the mid-1980s and has drafted or issued 77 individual CBM discharge permits. As of August 2009, there were 24 active CBM discharge permits in Alabama. ADEM indicated that conductivity and chlorides (both in CBM produced water and receiving streams) are of the greatest concern (ERG, 2009a). EPA reviewed the active CBM discharge permits; Table A-1 lists the monitored parameters, limits, and monitoring frequencies that were included in all the permits.

Table A-1. Alabama's Individual Permit Limitations

Parameter	Daily Minimum	Daily Maximum	Monthly Average	Monitoring Frequency
Flow- and Conductivity-Related Parameters				
Flow (mgd)	NA	Monitor	Monitor	Continuous
Conductivity	NA	Monitor	Monitor	Continuous
Metals				
Total Iron (mg/L)	NA	6	3	Weekly
Total Manganese (mg/L)	NA	4	2	Weekly
Other Pollutants				
BOD (mg/L)	NA	45	30	Weekly
Dissolved Chlorides (mg/L)	NA	Monitor	Monitor	Weekly
Dissolved Oxygen (mg/L)	5	NA	NA	Weekly
In-Stream Chlorides (mg/L)	NA	230	NA	Weekly
Oil and Grease (mg/L)	NA	15	NA	Weekly
pH (s.u.)	6	9	NA	Daily

NA – Not applicable.

Alabama's permits require permittees to continuously measure flow and conductivity and to use a continuous flow measurement device and an ADEM-approved discharge diffuser to limit chloride concentrations in the receiving stream. Permittees are required to submit and implement a Best Management Practices Plan to minimize the potential for accidental discharges of process liquids or solids.

Permittees must monitor conductivity and use the following correlation between conductivity and chlorides (chloride [mg/L] = conductivity × 0.287) to determine the amount of chlorides that can be discharged from the CBM well. Permittees are required to continuously monitor the conductivity and chloride concentrations both upstream and downstream from each CBM outfall in both the river and its tributaries. If chloride concentrations exceed 210 mg/L in the receiving stream or 190 mg/L in its downstream tributaries, permittees must cease discharging. The permits require monitoring of in-stream dissolved oxygen concentrations depending on the produced water discharge concentration. Permittees must also perform both 48-hour acute and short-term chronic WET tests at a minimum of once per quarter. Acute toxicity tests must result in greater than 90 percent survival; less than 90 percent survival indicates noncompliance. Chronic toxicity tests must result in greater than 80 percent survival.

Permittees are also required to monitor any stormwater discharges associated with construction and operation of their facilities. Monitored parameters for stormwater include flow, pH, total iron, total manganese, dissolved chlorides, BOD_5, COD, oil and grease, TSS, and turbidity. The discharge limit for turbidity is 50 n.t.u. above background levels in the receiving stream.

Colorado

For the past 10 years, Colorado has regulated all discharges to surface water (from approximately 20 CBM operations) under a general permit for produced water discharges from oil-and-gas-producing formations. However, the Colorado Department of Public Health and Environment (CDPHE) is currently reissuing all CBM permits as individual permits at the end of their respective permit cycles. CDPHE indicated that sodium is the primary issue of concern with CBM discharges in Colorado. Other concerns include dewatering of domestic wells, discharge of high volumes of water into dry creeks, downcutting, erosion, and an increase in sediment deposition (ERG, 2009b).

Colorado issued a new general permit for produced water discharges from oil-and-gas-producing formations in September 2009 for those CBM permittees yet to be covered by an individual permit. The limitations and monitoring requirements therein, effective September 2009, are based on state water quality standards, effluent and watershed limitations, and policies. Table A-2 lists the permitted parameters, limits, and monitoring frequencies included in Colorado's general CBM permit.

Table A-2. Colorado's General Permit Limitations

Parameter	Monthly Average	Weekly Average	Daily Maximum	Monitoring Frequency
Flow- and Conductivity-Related Parameters				
SAR	2.5 [a]	NA	NA	Weekly
Flow (mgd)	Limit	NA	Report	Continuous
Conductivity (dS/m)	0.70	NA	NA	Weekly
Metals				
Inorganic Metals (µg/L)	Site Specific	NA	Site Specific	Flow Based
Radium 226+228 (pCi/L)	NA	NA	5	Flow Based
Other Pollutants				
Benzene (µg/L)	NA	NA	Site Specific	Flow Based
Chloride (mg/L)	250	NA	NA	Flow Based
Ethylbenzene (µg/L)	NA	NA	Site Specific	Flow Based
Oil and Grease (mg/L)	NA	NA	10	Flow Based
Other Nonmetal Inorganic Chemicals (µg/L)	Site Specific	NA	Site Specific	Flow Based
Other Organic Chemicals (µg/L)	Site Specific	NA	Site Specific	Flow Based
Other Radionuclides (pCi/L)	Site Specific	NA	Site Specific	Flow Based
pH (s.u.)	NA	NA	6.5–9.0	Weekly
Sulfate (mg/L)	250	NA	NA	Flow Based
TDS (mg/L)	Site Specific	NA	NA	Weekly

Table A-2. Colorado’s General Permit Limitations

Parameter	Monthly Average	Weekly Average	Daily Maximum	Monitoring Frequency
Temperature (ºC)	NA	9.0–24.2	13.0–28.6	Flow Based
Toluene (µg/L)	NA	NA	Site Specific	Flow Based
Total Xylene (µg/L)	NA	NA	Site Specific	Flow Based
TSS (mg/L)	30	45	NA	Weekly

Note: “Flow Based” indicates that monitoring frequency is weekly (over 100,000 gpd), bimonthly (50,001–100,000 gpd) or monthly (less than 50,000 gpd) based on discharge volumes.
a – SAR of 2.5 is acceptable provided EC is 0.70.
NA – Not applicable.

The flow limit in the general permit is based on the design capacity of CBM produced water treatment process. Many parameters such as TDS, metals, and radionuclides are assigned on a site-specific basis, based on:

- Water quality standards in specific locations;
- Designed beneficial uses;
- Limitations for discharges to specific watersheds;
- Receiving water characteristics; and
- Produced water quality.

Colorado also requires a chronic WET test in which there can be no statistically significant differences between control and effluent concentrations.

Montana

The Montana Department of Environmental Quality (MTDEQ) has been issuing individual CBM permits since the mid-1990s, with the requirement that CBM discharges not be any more or less pure than the natural conditions of the receiving stream. Currently, there are three active CBM permits in Montana; however, EPA was able to review only two of them. Montana only has three operators, two of which do not discharge produced water directly. All three permits belong to the sole direct discharging operator, and those permits cover hundreds of wells. EC and SAR are of the biggest concern to Montana because typical surface waters have high levels of background salts, and increased concentrations of EC and SAR can precipitate the salt out of the waters. MTDEQ indicated that they are concerned with using CBM produced water for irrigation, through either the direct beneficial use of CBM waters or the use of surface waters influenced by upstream CBM discharges, as there is a potential for disaggregation of the soil. MTDEQ is also concerned about water rights and altered downstream conditions (ERG, 2009c).

Permit parameters found in both of the reviewed individual permits include EC, SAR, pH, oil and grease, TSS, TDS, total recoverable cadmium, total recoverable selenium, total recoverable mercury, and total recoverable arsenic. Both permits included summer (March through October) and winter (November through February) limits for EC and SAR, although the actual limits differed. Table A-3 lists the permitted parameters, limits, and monitoring frequencies included in Montana’s two reviewed CBM permits.

Table A-3. Montana's Individual Permit Limitations and Monitoring Frequencies

Parameter	Daily Minimum	Daily Maximum	Monthly Average	Monitoring Frequency
Flow- and Conductivity-Related Parameters				
SAR	NA	Mar–Oct: 2.6/4.5 Nov–Feb: 6.6/7.5	Mar–Oct: 1.3/3.0 Nov–Feb: 3.3/5.0	Weekly, Monthly
Flow (mgd)	NA	Apr–Aug: 0 Sep–Mar: 0.19–0.32/NA	NA	Continuous
Conductivity (μS/cm)	NA	Mar–Oct: 964/1,500 Nov–Feb: 1,265/2,500	Mar–Oct: 480/1,000 Nov–Feb: 631/1,500	Continuous, Monthly
Metals				
Dissolved Aluminum (mg/L)	NA	NA	NA	Semiannual
Calcium (mg/L)	NA	NA	NA	Weekly
Magnesium (mg/L)	NA	NA	NA	Weekly
Sodium (mg/L)	NA	NA	NA	Weekly
Total Recoverable Arsenic (mg/L)	NA	Cannot exceed upstream concentrations/ NA	NA	Monthly/Semiannual
Total Recoverable Barium (mg/L)	NA	NA	NA	Semiannual
Total Recoverable Cadmium (mg/L)	NA	0.48/NA	0.054/NA	Monthly/Semiannual
Total Recoverable Copper (mg/L)	NA	NA	NA	Semiannual
Total Recoverable Iron (mg/L)	NA	NA	0.6	Weekly, Monthly
Total Recoverable Lead (mg/L)	NA	NA	NA	Semiannual
Total Recoverable Manganese (mg/L)	NA	NA	NA	Semiannual
Total Recoverable Mercury (mg/L)	NA	Cannot exceed upstream concentrations/ NA	NA	Monthly/Semiannual
Total Recoverable Radium (pCi/L)	NA	Cannot exceed upstream concentrations	NA	Monthly
Total Recoverable Selenium (μg/L)	NA	3.0	0.75	Monthly
Total Recoverable Zinc (mg/L)	NA	NA	NA	Semiannual
Total Strontium (mg/L)	NA	NA	NA	Semiannual
Other Pollutants				
Ammonia (mg/L)	NA	0.26	0.13	Weekly, Semiannual
BOD (mg/L)	NA	NA	N/A	Semiannual
Nitrite and Nitrate (mg/L)	NA	NA	NA	Semiannual
Oil and Grease (mg/L)	NA	10	NA	Monthly

Table A-3. Montana's Individual Permit Limitations and Monitoring Frequencies

Parameter	Daily Minimum	Daily Maximum	Monthly Average	Monitoring Frequency
pH (s.u.)	6.5	9.0/8.4	NA	Continuous, Weekly/Daily
TDS (mg/L)	NA	NA	NA	Weekly, Monthly
Temperature (ºF)	NA	NA	NA	Continuous, Weekly
Total Cyanide (mg/L)	NA	NA	NA	Semiannual
Total Kjeldahl Nitrogen (mg/L)	NA	NA	NA	Semiannual
Total Nitrogen (mg/L)	NA	NA	NA	Semiannual
Total Phenols (mg/L)	NA	NA	NA	Semiannual
Total Phosphorus (mg/L)	NA	NA	NA	Semiannual
Total Recoverable Boron (mg/L)	NA	NA	NA	Semiannual
Total Recoverable Fluoride (mg/L)	NA	NA	0.5	Weekly, Monthly
TSS (mg/L)	NA	40/30	17/25	Monthly/Weekly

NA – Not applicable.

Pennsylvania

CBM development began in Pennsylvania in the 1970s and began increasing in the mid-1990s, especially in southwestern Pennsylvania. The Pennsylvania Department of Environmental Protection (PADEP) currently has 12 active CBM individual permits, eight pending permits, and five permits pending renewal with varying site-specific monitoring and discharge limitations. EPA, however, was unable to review any of these permits and received all data concerning these permits via telephone conversations with PADEP staff. PADEP indicated that CBM produced water is not of good quality and it is most concerned with elevated levels of chlorides and iron in the water. Pennsylvania currently sets discharge limits for TDS, iron, flow, TSS, oil and grease, and osmotic pressure and requires monitoring of acidity, alkalinity, and chlorides (ERG, 2009d).

West Virginia

The West Virginia Department of Environmental Protection (WVDEP) has issued two individual permits for CBM produced water direct discharge to surface waters; however, neither of the operations has actually discharged produced waters. One operator reported surface water discharge in the screener survey, and possibly holds a permit, but apparently has not discharged produced water yet (the operator reported a number of other management practices) (U.S. EPA, 2010a). In West Virginia, CBM operations tend to land apply their produced waters rather than discharge to surface waters and might occasionally discharge to a POTW (ERG, 2009e). One operator indicated in the screener survey that indirect discharge is one method they use (U.S. EPA, 2010a). Land application permits are handled under a general permit by West Virginia's Office of Oil and Gas. EPA was unable to determine how many land application permits have been issued to CBM operations, although two operators in EPA's screener survey indicated that they do practice land application of produced water (U.S. EPA, 2010a).

Wyoming

The Wyoming Department of Environmental Quality (WYDEQ) began issuing individual CBM discharge permits in the mid-1990s, with the majority issued within the past 10 years. WYDEQ has issued approximately 1,000 CBM permits, with approximately 800 current permits. As these individual CBM permits expire, WYDEQ plans to reissue them as watershed-based permits because there can be several dozen CBM dischargers in a given watershed (ERG, 2009f). Currently, WYDEQ has issued about 11 watershed-based permits. Wyoming's watershed-based permitting program is focusing on areas with increasing or heavy CBM development.

WYDEQ identified TDS, EC, SAR, dissolved iron, total recoverable arsenic, barium, cadmium, and selenium as constituents of concern and has set permit limits for each of these constituents. WYDEQ is concerned about stream downcutting and flooding associated with large-volume discharges, but does not have a regulatory mechanism to control CBM discharge volumes (ERG, 2009f).

EPA reviewed Wyoming's 11 watershed-based permits and determined that limits varied by the type of discharge category, of which there are four based on the type of receiving water body and containment practices:

- Category 1—direct discharges to stream channels with no containment requirements.
- Category 2—discharges are contained in on-channel reservoirs with regular overtopping of stream banks due to precipitation allowed.
- Category 3—discharges to on-channel headwater reservoirs or playa lakes with required containment for the 50-year or 100-year 24-hour storm event.
- Category 4—discharges to constructed off-channel pits. These discharges are not allowed under the watershed permits and require individual permits.

All watershed-based permits contain identical general language prohibiting the following: the discharge of floating solids; any visible foam or sheen; discharges that cause erosion, scouring, or damage to the outfall stream; discharges that cause aesthetic or habitat degradation; and discharge of toxic substances.

Table A-4 lists Wyoming's watershed-based permit limitations by discharge category. In addition to the discharge limits and prohibitions, Wyoming has watershed-specific monitoring requirements including monitoring of steam headcuts, channel stability station monitoring, water quality station monitoring, WET testing, Category 2 flow monitoring, downstream irrigation monitoring, and Category 1 stream flow limits.

Table A-4. Wyoming's Watershed-Based Permit Limitations by Discharge Category

Parameter	Category 1 Daily Maximum	Category 2 Daily Maximum	Category 3 Daily Maximum	Category 4 [a] Daily Maximum	Measurement Frequency
Flow- and Conductivity-Related Parameters					
SAR	1 -13, SAR < 7.10 × EC – 2.48	8–10	NA	NA	Biweekly–Annually
Flow (mgd)	0.36–9.70	NA	NA	NA	Monthly–Annually
Conductivity (μmohs/cm)	450–7500	1330–7500	7500	7500	Biweekly–Annually
Metals					
Dissolved Cadmium (μg/L)	0.1–4.0	0.6–4	NA	NA	Annually
Dissolved Calcium (mg/L)	NA	NA	NA	NA	Biweekly–Annually
Dissolved Copper (μg/L)	4–13.2	10	NA	NA	Annually
Dissolved Iron (μg/L)	74–1000	300–1000	1000	NA	Every 3 mo.–Annually
Dissolved Lead (μg/L)	2–4	2–4	NA	NA	Annually
Dissolved Magnesium (mg/L)	NA	NA	NA	NA	Biweekly–Annually
Dissolved Manganese (μg/L)	50	NA	NA	NA	Annually
Dissolved Silver (μg/L)	7.5	NA	NA	NA	Annually
Dissolved Sodium (mg/L)	60–170	NA	NA	NA	Biweekly–Annually
Dissolved Zinc (μg/L)	80–100	80–100	NA	NA	Annually
Total Radium 226 (pCi/L)	3	NA	60	60	Annually
Total Radium 226 + Total Radium 228 (pCi/L)	1–60	5	NA	NA	Annually
Total Recoverable Aluminum (μg/L)	490–750	NA	750	NA	Annually
Total Recoverable Arsenic (μg/L)	2.4–8.4	7–10	150–180	150	Annually
Total Recoverable Barium (μg/L)	360–1800	1800–2000	1800	1800	Annually
Total Recoverable Selenium (μg/L)	2–5	5	NA	NA	Annually
Other Pollutants					
Ammonia (mg/L)	0.4–6.8	NA	NA	NA	Weekly–Annually
Bicarbonate (mg/L)	NA	NA	NA	NA	Monthly–Annually
Chlorides (mg/L)	50–230	150–230	230–2000	230–2000	Monthly–Annually
Dissolved Boron (μg/L)	NA	NA	NA	NA	Annually
Dissolved Fluoride (μg/L)	2000–4000	4000	2000–4000	2000–4000	Annually

Table A-4. Wyoming's Watershed-Based Permit Limitations by Discharge Category

Parameter	Category 1 Daily Maximum	Category 2 Daily Maximum	Category 3 Daily Maximum	Category 4 [a] Daily Maximum	Measurement Frequency
pH (s.u.)	6.5–9.0	6.5–9.0	6.5–9.0	6.5–9.0	Monthly–Annually
Sulfate (mg/L)	412–3000	NA	3000	3000	Biweekly–Annually
TDS (mg/L)	300–5000	NA	5000	5000	Biweekly–Annually
Temperature (ºC)	NA	NA	NA	NA	Monthly–Every 6 mo.
Total Alkalinity (mg/L)	NA	NA	NA	NA	Monthly–Annually

a – Category 4 discharges require an individual permit. Limits are displayed here for comparison purposes.
NA – Not applicable.