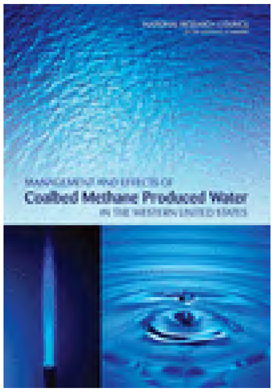

Management and Effects of Coalbed Methane Produced Water in the United States

Committee on Management and Effects of Coalbed Methane Development and Produced Water in the Western United States; Committee on Earth Resources; National Research Council

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Committee on Management and Effects of Coalbed Methane Development and Produced Water in the Western United States

Committee on Earth Resources

Board on Earth Sciences and Resources

Water Science and Technology Board

Division on Earth and Life Studies

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Cover: The images of natural gas and water illustrate the need to consider management of two resources important to the United States and particularly to the arid West. Cover design by Anne Rogers.

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Preface

The committee has approached this congressionally mandated task to examine the management of coalbed methane (CBM) produced water in six western states within a national context of increasing demand to develop domestic energy resources in environmentally and economically viable ways. The production of CBM for use as an energy source requires pumping water from coalbeds to release methane from the coal surfaces. The CBM "produced water" that results from this pumping process is managed through treatment, storage, disposal, and/or use, under a complex set of federal and state regulations.

Although produced water and its management are common to the majority of oil and gas production activities, CBM produced water has been the subject of specific, recent attention for several reasons: (1) the CBM industry is relatively young—with most operations in the western United States only producing methane since the 1990s—and development has been rapid in several regions; (2) the length of time to observe and understand potential effects on the environment from CBM produced water has been correspondingly brief; (3) the relatively low salinity of some CBM produced water has allowed consideration of this water for various practical uses in the arid West; and (4) litigation within and among states, citizens, and industry sharing CBM basins and watersheds has resulted from differing approaches to CBM produced water management.

To address the study, the committee reviewed documents produced by federal and state agencies and consultants, peer-reviewed literature, online databases and resources, and information requested from and submitted by external sources, including three public meetings and six public teleconferences. The committee held its public meetings in Washington, D.C.; Denver, Colorado; and Santa Fe, New Mexico. Each public meeting included dialogue with the study sponsor, the Bureau of Land Management, other federal and state agencies, academic and national laboratory researchers, and industry representatives who addressed various points of the committee's study charge. An opportunity for public input was provided at the committee meeting in Denver.

The committee was sensitive to the interest in understanding the effects of CBM produced water on the environment when it is treated and released for disposal or might be used for any beneficial purposes. The committee was thus conscientious in its efforts to identify and distinguish between scientifically and technically documented effects of CBM produced water on the environment; those effects that may be considered "potential" effects through laboratory studies, for example, but without field documentation; and reports of effects that do not yet have enough supporting data or independent analysis to determine cause. In a comparable way, hydraulic fracturing was not a specific item the committee was tasked to address but was a topic raised to the committee's attention during the course of this study. Hydraulic fracturing uses fluid injection to stimulate oil and gas production in many oil and gas wells but is employed rarely, or not at all, in CBM operations where coal seams are relatively near to the surface and have correspondingly high initial water contents. Without a direct link between hydraulic fracturing and the largest volumes of CBM produced water that are managed in the West, the committee addressed hydraulic fracturing only briefly in the report.

Throughout its examination of CBM produced water management, the committee has assumed that operators, regulatory agencies, water treatment companies, and private citizens alike use appropriate and professional procedures in their operations and in their management of produced water. The committee has thus focused its efforts on ways in which the current regulatory, legal, environmental, energy, and economic framework functions with respect to management of produced water from CBM operations and how this framework could be supported and improved. Nonetheless, in some instances data and information have demonstrated that "best practices" have not been followed in the management of CBM produced water and the committee has noted the situations which came to our attention.

As demands continue to couple energy resource development with environmental stewardship, demands for water resources and effective management of water for multiple uses will likewise continue to grow. In this context, an examination of CBM produced water management is timely, and the committee hopes this report informs the decision-making process with respect to important energy and water resources.

William Fisher
Chair

Acknowledgments

In addition to its own expertise, the committee relied on input from numerous external professionals and members of the public with extensive experience in various aspects of coalbed methane development and produced water management. All of these individuals provided presentations, data, analyses, and illustrative figures and images which assisted the committee in understanding the scope of the issue and the roles played by federal, state, and tribal governments and agencies, the private sector, non-governmental organizations, research organizations, and the public. This information was very important to the committee in formulating the report. We gratefully acknowledge these individuals, and note particularly their prompt and thorough responses to our inquiries throughout the study's course. In particular, the committee would like to thank the following individuals: Troy Bauder, Doug Beagle, Diedre Boysen, John Boysen, Curtis Brown, David Brown, James Burd, Aïda Farag, Mark Fesmire, Don Fischer, Carol Frost, Carey Johnston, James Keener, David Mankiewicz, Vince Matthews, Elizabeth Meredith, Terrance Olson, Kevin Rein, Ashley Roberts, Kathy Shreve, Timothy Spisak, Carrie Steinhorst, David Stewart, Jason Thomas, Ralf Topper, John Veil, John Wheaton, and Michael Wireman.

This report has been reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise, in accordance with procedures approved by the National Research Council's (NRC) Report Review Committee. The purpose of this independent review is to provide candid and critical comments that will assist the institution in making its published report as sound as possible and to ensure that the report meets institutional standards for objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process. We wish to thank the following individuals for their participation in the review of this report:

David Burnett, Texas A&M University, College Station

Debra L. Donahue, University of Wyoming, Laramie
Jörg E. Drewes, Colorado School of Mines, Golden
Gretchen K. Hoffman, New Mexico Bureau of Geology and Mineral Resources, Socorro
Lawrence Y.C. Leong, Kennedy/Jenks Consultants, Irvine, California
Thomas Meixner, University of Arizona, Tucson
Dianne R. Nielson, State of Utah, Salt Lake City
Russell E. Stands-Over-Bull, Anadarko Petroleum Corporation, Golden, Colorado
George Vance, University of Wyoming, Laramie
John Veil, Argonne National Laboratory, Washington, D.C.

Although the reviewers listed above provided many constructive comments and suggestions, they were not asked to endorse the conclusions or recommendations nor did they see the final draft of the report before its release. The review of this report was overseen by William S. Condit, Independent Consultant, Santa Fe, New Mexico and Michael C. Kavanaugh, Malcom Pirnie, Inc. Emeryville, California. Appointed by the NRC, they were responsible for making certain that an independent examination of this report was carried out in accordance with institutional procedures and that all review comments were carefully considered. Responsibility for the final content of this report rests entirely with the authoring committee and the institution.

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APPENDIXES

Summary

In some coalbeds, naturally occurring water pressure holds methane—the main component of natural gas—fixed to coal surfaces and within the coal. In a coalbed methane (CBM) well, pumping water from the coalbeds lowers this pressure, facilitating the release of methane from the coal for extraction and use as an energy source. Water pumped from coalbeds during this process—CBM "produced water"—is managed through some combination of treatment, disposal, storage, or use, subject to compliance with federal and state regulations.

CBM produced water management can be challenging for regulatory agencies, CBM well operators, water treatment companies, policy makers, landowners, and the public because of differences in the quality and quantity of produced water; available infrastructure; costs to treat, store, and transport produced water; and states' legal consideration of water and produced water. Some states consider produced water as waste, whereas others consider it a beneficial byproduct of methane production. Thus, although current technologies allow CBM produced water to be treated to any desired water quality, the majority of CBM produced water is presently being disposed of at least cost rather than put to beneficial use.

The Energy Policy Act of 2005 (P.L. 109-58, Section 1811) noted the relevance of CBM produced water and directed the Bureau of Land Management (BLM) to enter into an agreement with the National Research Council (NRC) to evaluate CBM produced water management in six western states. The NRC established the Committee on Management and Effects of Coalbed Methane Development and Produced Water in the Western United States to develop this report, which addresses the study charge (Box S.1).

The report specifically examines the Powder River, San Juan, Raton, Piceance, and Uinta CBM basins in the states of Montana, Wyoming, Colorado, New Mexico, and Utah. The report's conclusions and recommendations identify:

- gaps in data and information about the natural variations in CBM produced water quality and quantity, baseline conditions and the effects of CBM produced water

on the environment, and the degree of connectivity among water-bearing coalbeds, other groundwater aquifers, and surface water;
- potential beneficial uses of CBM produced water and costs for various water treatment, storage, or use strategies;
- documented and potential effects of CBM produced water on surface and groundwater resources, soil, and ecological systems and ways in which those effects could be monitored and mitigated; and
- challenges in the existing regulatory framework for CBM produced water management.

Although directed toward CBM basins in the arid West, the report bears on CBM production and produced water issues in other CBM basins in the United States. To date, no

BOX S.1
Statement of Task

This study will examine the effects of CBM development and produced water on water and soil resources in the western states of Colorado, Montana, New Mexico, Utah, North Dakota, and Wyoming. Specifically, the study will:

(1) Briefly review existing and ongoing studies by federal agencies related to CBM produced water effects and management including water treatment, use, storage, and disposal; environmental (natural and human) effects; and water quality and quantity.
(2) Identify the major federal and state data resources available for CBM produced water management including those available for topics in (1), above, and identify the major factors influencing CBM produced water chemistry and potential toxicity; the baseline data necessary for effective management of CBM produced water; data gaps, if any, and any additional need for data.
(3) Identify the major positive and negative effects of CBM produced water treatment, use, storage, and disposal on the quality and quantity of surface and ground water resources, including environmental effects documented by public and private stakeholders.
(4) Review existing federal and state regulations that address the management and potential effects of CBM produced water on surface and ground water resources.
(5) Evaluate the effectiveness of current and emerging best management practices and production techniques for CBM produced water management options in terms of the minimization of potential negative impacts to water resources.
(6) Discuss the costs for produced water management options, including existing and emerging techniques used in water treatment, use, storage, and disposal.

When evaluating the effects of CBM development on water resources, relevant geological, geochemical, hydrological, ecological, environmental, social, and health factors, water rights issues, and historical and projected CBM production volumes will be considered.

national consensus has been reached on clearly defined goals, objectives, management positions, or policies that take into account potential environmental effects of CBM produced water *and* allow for consideration of a range of potential beneficial use options. Resolving these gaps could increase the ability of public and private stakeholders to develop effective and environmentally and economically sound CBM development and produced water management strategies and practices.

NATURAL VARIATIONS IN CBM BASINS

Quality and quantity of CBM produced water, determined largely by the natural geologic and hydrologic characteristics of each CBM basin, are among the primary factors determining produced water management strategies and potential and actual effects of produced water on the environment. The degree of connectivity ("hydraulic connectivity") among water-bearing coalbeds which are the targets of CBM production, overlying and underlying aquifers, other shallow groundwater aquifers, and surface water is also important. Hydraulic connectivity affects how water in coalbeds and surrounding sedimentary rocks moves and replenishes through time and has consequences for the effects of produced water withdrawals. Water that has not been replenished for a long time—from human lifetimes to millions of years—is termed "old" or "fossil" water and can be considered a nonrenewable resource.

The coalbeds used for CBM in the Powder River Basin of Wyoming and Montana are generally more porous and permeable and yield relatively fresher produced waters[1] than the more deeply buried, methane-bearing coalbeds in the CBM basins of New Mexico, Colorado, and Utah. The high porosity and permeability in Powder River coalbeds also require larger volumes of water to be withdrawn by the CBM well operator to stimulate methane release from the coal, compared to the other western CBM basins. Large volumes of relatively fresh CBM produced water from the Powder River Basin are then primarily managed through discharge to surface storage impoundments or to ephemeral and perennial streams and rivers, with or without treatment to meet regulatory requirements. A limited amount of produced water is put to beneficial use. In contrast, smaller volumes of generally very saline CBM produced waters from basins in New Mexico, Colorado, and Utah are primarily managed through disposal by deep-well reinjection.

A suite of geological, geophysical, and geochemical data which includes "age dating" of CBM produced water is needed to establish the degree of hydraulic connectivity between

[1]In discussing the chemistry of CBM produced water, the committee sometimes uses the qualifying word "relatively" to denote differences in the total dissolved solids (TDS), salinities, and sodicities of CBM produced waters as they vary across the western basins. For example, CBM produced water from the Powder River Basin is sometimes described as "relatively fresh," whereas CBM produced water from the San Juan Basin may be described as having "relatively high salinity." The report provides the background for the use of these terms.

CBM production targets, other groundwater aquifers, and surface waters. These types of data have been collected and analyzed from the San Juan Basin and show that CBM produced water from this basin is fossil water. Similarly comprehensive data to determine whether or not the CBM produced water from other western CBM basins is fossil water have not been collected.

Lack of knowledge of the age of CBM produced water contributes to uncertainty in understanding the consequences of long-term produced water withdrawals to other aquifers. At present, the "age" of CBM produced water and consideration of fossil CBM produced water as a nonrenewable resource are not currently factored into decisions about produced water management strategies. **Determining the age of CBM produced water and therefore its "renewability" should be included in the development and implementation of CBM produced water management regulations.**

Groundwater modeling can also be used to characterize some aspects of groundwater resources, including hydraulic connectivity. However, these models are not able to incorporate the full range of natural complexities in CBM basins. A combination of sensitivity analysis, history matching, and multiple lines of calibration is needed to quantify the level of uncertainty of model predictions and to provide a level of reliability for the model results. **The uncertainties in groundwater modeling results should be explicitly recognized when the results are used to make produced water management and regulatory decisions.**

CBM PRODUCED WATER TREATMENT TECHNOLOGIES, COSTS, AND BENEFICIAL USES

In addition to produced water quality and quantity, other determinants that weigh into the decision of whether CBM produced water is treated, disposed, stored, or put to beneficial use include: (1) quality and reliability of sustained produced water supply over time; (2) treatment costs; (3) proximity of location of produced water to the proposed beneficial use (such as irrigation); (4) costs and infrastructure for water transport and storage; (5) degree of compatibility between produced water quality and potential receiving landscapes or water bodies; (6) availability of suitable storage and disposal sites; and (7) the legal framework for application of produced water to beneficial uses.

Several treatment technologies with extensive performance history have proven effective in the western CBM basins. However, in nearly all cases where CBM produced water is treated, the degree of water treatment is driven by regulatory requirements for disposal or permitted discharge rather than for the purpose of achieving quality for beneficial use.

Options for disposal and storage include deep-well reinjection, storage in lined or unlined surface impoundments for evaporation or for percolation into underlying soil, direct discharge to ephemeral or perennial surface waters, and land-applied water spreading and managed surface irrigation. Potential beneficial use applications for CBM produced water include livestock and wildlife watering, subsurface drip irrigation, instream flow augmentation, wetlands augmentation, and industrial and municipal uses. In concept and on paper, putting CBM produced water to beneficial use would thus seem to be a desirable and relatively easy objective. In reality, management or discharge of CBM produced water for the specific purpose of achieving beneficial use is potentially economically and environmentally burdensome, complex, and challenging.

The production, handling, management, and disposal of produced water all contribute to the cost of production of methane from coalbeds, and CBM produced water rarely, if ever, constitutes an income stream for energy producers. Even where CBM produced water is intentionally put to beneficial use, the cost of implementation of such use almost universally exceeds any realized economic gain in the current regulatory and economic climate. These factors have contributed to a varied range of treatment, disposal, and storage options being employed in the western CBM basins, and within the same basin in different states, with only a small proportion of the produced water being put to beneficial use.

ENVIRONMENTAL EFFECTS OF CBM PRODUCED WATER

Concerns about environmental effects associated with CBM production and produced water management relate primarily to short- and long-term consequences of (1) groundwater depletion and drawdown associated with water pumping during CBM extraction, and (2) the disposal, storage, management, and permitted discharge of produced water, which may affect groundwater and surface water quantity and quality, soil and agricultural development, and ecological systems.

Groundwater Quantity and Quality

The extent of groundwater drawdown in the coalbeds from which CBM has been extracted depends on the overall volume of water in the coalbed and hydrogeology of the basin, the density of CBM wells, the rate of water pumping by the operator, the rate of recharge of the coalbeds from surrounding sediments and coals, and the length of time pumping takes place. The time for the CBM-bearing aquifer to return to its original water pressure or level depends upon the extent of drawdown and the volume of water pumped, porosity and permeability of and depth to the coalbed, climatic and seasonal conditions, and connectivity to sources of water recharge.

In the Powder River Basin, drawdown of water levels and hydrostatic heads in coalbed aquifers has been documented as a result of CBM production. In the Montana portion of the basin, 65 to 87 percent recovery of coalbed groundwater levels has occurred after CBM production ceased, although the source of this recharge water remains uncertain. However, drawdown of water levels in shallow alluvial and water table aquifers has not been measured in the Powder River Basin as a result of CBM development. The degree to which drawdown in these Powder River coalbed aquifers might influence other shallow aquifers also remains unknown, in part due to insufficient data showing connectivity between coalbeds and other shallow groundwater aquifers. CBM extraction in the San Juan, Raton, Uinta, and Piceance basins is unlikely to cause lowering of the water table in shallow aquifers due to the great vertical distance and very limited connectivity between the deep coalbeds and shallow groundwater systems.

Resource management or regulatory agencies should require or continue to require collection of baseline groundwater level and quality information for domestic water wells in advance of new CBM drilling activities to protect well operators and residents. These data will give a baseline against which future water level and quality measurements can be compared.

In surface impoundments containing CBM produced water, infiltration and percolation of produced water can dissolve and mobilize preexisting salts or naturally occurring constituents such as sulfate, selenium, arsenic, manganese, barium, chloride, nitrate, and total dissolved solids in soils below the impoundments. In the Powder River Basin of Wyoming where impoundments provide the primary management method for CBM produced water, groundwater monitoring showed increased levels of total dissolved solids (TDS), selenium, sulfate, chloride, and/or nitrate downgradient of CBM produced water impoundments in approximately one third of the impoundments for which monitoring data are collected. The majority of impoundments studied had no apparent change in groundwater quality and improved water quality was documented beneath a small fraction of the impoundments.

The differences among individual impoundments including (1) the substrate (soil or bedrock) on which the impoundment is constructed; (2) the volume of the impoundment and produced water entering the impoundment over time; (3) the transport path of the produced water to the impoundment (whether through a pipe or over land); (4) the length of time the water is in the impoundment; and (5) the local climate, influence how produced water may affect the groundwater beneath the impoundment. A groundwater monitoring network and the capacity to maintain and analyze results from such a network are considered important for use and management of CBM produced water impoundments that are used for more than temporary storage. **Groundwater monitoring downgradient of impoundments used for disposal of CBM produced water before, during, and after water storage in the impoundments should be conducted. The data from these installations should be enhanced with (1) data on the volumes and chemistry of water discharged into impoundments, and (2) evaluation of the effects of impoundment infiltration or seepage on downgradient groundwater and nearby surface water.**

Surface Water Quantity and Quality

At present, little evidence exists to show that surface water has been depleted by pumping water during CBM production at the *large watershed scale* in the San Juan or the Powder River basins. Managed discharge of CBM produced water to ephemeral and perennial streams and rivers otherwise occurs only in the Powder River Basin (Wyoming and Montana) and the Colorado portion of the Raton Basin. However, too few data exist to evaluate positive or negative effects to increased water flows in streams and rivers in these basins as a result of these discharges.

Physical effects to ephemeral or perennial streams and rivers, such as bank scouring, increased bottom sedimentation, or channel erosion due to unmanaged and/or unregulated CBM produced water discharge have occurred in the Powder River and the Raton basins. Regulatory authorities have required operators to control and discontinue practices or events contributing to these circumstances, and the committee supports all efforts to prevent unmanaged and unregulated releases of CBM produced water. Although little published evidence exists of any widespread effects of dynamic alteration in ephemeral stream channels due to regulated, controlled, and managed CBM produced water discharges, **regulated (managed and controlled) releases to perennial and ephemeral streams and rivers and directly to the landscape should be accompanied by pre-release monitoring of landscape features, including stream channels. Regular monitoring of the same landscapes is necessary after releases have commenced.**

Measurements of the effects of CBM produced water discharges on the chemistry of a receiving stream can be used to regulate the discharge quantity and quality, if needed, to comply with permit requirements and predict anticipated needs for treatment, disposal, management and use of produced water. **Measurements of the effects of CBM produced water discharges on receiving stream quality and quantity should be continued and rigorously used in setting regulatory requirements and permit limits by the appropriate state and federal authorities.** However, actual volumes of water being produced at CBM outfalls at most sites vary as a normal function of CBM well operations; produced water volume and chemistry data at outfalls are either infrequently collected, or not readily known or reported in an easily-accessible database.

In monitoring compliance, in modifying discharge allowances and permitted conditions, and in setting regulatory requirements, measurement of CBM produced water volumes and chemistry at outfalls should be collected regularly and used rigorously. Such data should be maintained and made publicly accessible as a collaborative endeavor among industry, and state and federal authorities.

To date, studies conducted on the effects of CBM produced water discharge on perennial stream water quality, which usually have only included measurements of total dissolved solids and sodium concentrations, yield equivocal results and these measurements may not be the best way to determine the influence of CBM produced water on receiving water bodies. Published research using isotope ratios of solutes in CBM produced water has shown that isotopic "fingerprints" of CBM water in receiving streams and rivers have changed as a result of CBM produced water discharge and may be more effective in monitoring and assessing CBM produced water influence on surface water and groundwater resources. **An array of chemical parameters, including major, minor, and trace constituents and isotopes, should be used to evaluate the potential effects of CBM discharges on stream water quality.**

Soil Quality and Agricultural Applications

Use of some CBM produced water for local irrigation in the Powder River Basin appears practical given appropriate conditions including availability of produced water and use of various combinations of selective application to nondispersive soils; treatment, dilution or blending of CBM produced water with other water sources; amendment of produced water and soils to be irrigated; and appropriate timing of irrigation practices. However, application of CBM produced water to some soils in the basin has altered plant ecology and resulted in adverse soil ecological, chemical, and hydrologic consequences particularly with respect to the influence of sodium in CBM produced water on soils and plants. In circumstances where CBM produced water is applied to soils, and also after use of CBM produced water ceases, additional soil management may be required to restore agricultural soil resources and impoundment sites to conditions that existed prior to CBM produced water application.

The degree of soil management required with application of CBM produced water is dependent on a number of factors—variable to the site and circumstances. The two most significant factors are the soil type and the quality of the CBM produced water, especially with respect to the sodium content. Considering that irrigation with CBM produced water containing relatively low total dissolved solids and constituent concentrations (such as the water sourced from the Powder River Basin and the Colorado portion of the Raton Basin) continues to be a contentious and challenging issue, CBM water sourced from some of the other western basins is unlikely to be suitable for irrigation without significant treatment.

Ecological Effects

A number of controlled laboratory and modeling efforts have been published that examined the potential effects of CBM produced water on some aquatic organisms. Laboratory studies indicate that exposure to elevated concentrations of total dissolved solids, bicarbonate, potassium, magnesium, chloride, and/or sulfate constituents that may occur in CBM produced water can be toxic to some freshwater organisms. Most laboratory comparisons are based on mean concentrations of discharges of CBM produced waters and on direct and prolonged exposure of conventional laboratory test species to undiluted, untreated CBM produced water or its constituents.

To date, widespread adverse effects on indigenous organisms and vegetation as a result of changes in surface water chemistry due to CBM produced water discharges in the field have not been widely studied or demonstrated. A few field tests conducted in the Powder River Basin showed mortality to some species when levels of bicarbonate exceeded the thresholds established in laboratory tests, while two other field studies noted difficulty in identifying any direct effects of CBM discharges on fish assemblages. **Studies to evaluate the extent and persistence of changes in water chemistry and ecological effects on indigenous species and hydrological systems *in the field*, including perennial riparian vegetation, stream hydrological function, stream channel geomorphology, macroinvertebrates, nutrient loading, and fisheries, should be conducted. The results should be used as input to review and enhance, as needed, CBM produced water management, treatment, and disposal requirements.**

REGULATORY FRAMEWORK FOR CBM PRODUCED WATER MANAGEMENT

At the federal level, the requirements associated with leasing and permitting CBM operations on federally managed public lands through the BLM and the protection of water resources under the jurisdiction of the Environmental Protection Agency (EPA) are relatively broad but clear. State regulations regarding treatment and management of CBM produced water differ among the states examined in this study, as do the degrees to which the states have been delegated primacy by federal agencies for permitting and regulating management of CBM produced water. Recognizing the jurisdiction of Indian tribes in regulating CBM development and in CBM produced water management is also important. Surface water discharges of produced water on federal, state, tribal, and private lands is typically managed by state or tribal primacy programs under the Clean Water Act, while discharges to the subsurface environment, including deep-well reinjection and subsurface drip irrigation, are typically managed under the Safe Drinking Water Act by state or tribal primacy programs.

At present, a challenge to the effective management of produced water is the inconsistency in the regulatory consideration and legal description of CBM produced water as a waste or as a resource and the inconsistent definition of terms such as "beneficial use." CBM produced water volumes change over time and eventually decrease to near zero as CBM fields mature, making sustainability of the water resource an issue to consider for beneficial use opportunities. The committee concludes that management of CBM produced water is presently driven by the economics of disposal and treatment costs and regulations rather than consideration of its possible beneficial use.

Given that produced water can be treated to any water quality with current technologies, but at varying costs, **future regulation of CBM produced water management should consider the age of the CBM produced water. Careful management of non-renewable "fossil" water should be considered a priority.** Management of a water resource that is indeed irreplaceable may benefit from considering opportunities to put it to best use or to store it in aquifers for future use, rather than to dispose of it. Current regulations and water law do not provide incentives to CBM operating companies (or other stakeholders) to put produced water to beneficial use or offer many options to consider other than to dispose of nonrenewable CBM produced water. Although a number of recent court reviews of CBM production activities do signal some recognition of the fact that water resources naturally traverse state, legal, and geological boundaries, these reviews have not provided clarification about effective produced water management and instead exemplify state-specific approaches.

CLOSING REMARKS

The coupled demands for domestic energy and clean water resources require the environmentally and economically sound management of produced water from CBM activities. The most important aspect of this issue is the science surrounding the use or disposal of CBM produced water. Multiple potential users and uses of limited water resources, a concern by the public for protection of these limited resources, the complexities of hydrogeological systems, and the renewability or nonrenewability of water resources require increasingly sophisticated approaches to understanding CBM produced water and produced water management. These approaches require a basis in scientifically grounded studies and consistent monitoring, and should allow for a greater range of economically and environmentally viable options for CBM produced water management in the future.

CHAPTER ONE

Methane and Water in Coalbeds

Methane production from coalbeds involves management of two important national resources: energy, in the form of natural gas, and water. In a coalbed methane (CBM) well, pumping water from the coalbeds lowers natural water pressure in the coalbed and allows the methane that had been fixed to the coal surfaces to be released and extracted (Figure 1.1). Water pumped from coalbeds as part of this process—CBM "produced water"—ranges widely in quality and quantity and is managed through some combination of treatment, storage, disposal, and/or use, subject to compliance with federal, state, and tribal regulations.

At present, significant differences exist in CBM produced water management strategies among states and between basins in the same state. These differences are due in part to differences in the composition and volume of produced water; the geology and hydrogeology of the CBM basins; federal, state, and tribal regulations; the legal categorization of water and water rights by government authorities; and costs to treat, store, and transport produced water. Produced water management is thus a challenge for regulatory agencies, CBM well operators, water treatment companies, policymakers, and the public.

Particularly in the arid western United States, water resources are scrutinized by many public and private concerns because of the need for water in such varied applications as agriculture, ranching, municipal and industrial consumption, and maintenance of natural habitats. In 12 western states[1] more than 80 billion gallons of water (~245,000 acre-feet) per day were withdrawn from both surface and groundwater resources in 2005 for irrigation purposes alone (Barber, 2009). This is equivalent to completely filling about 100 domed

[1]Western states cited include Washington, Oregon, California, Idaho, Nevada, Arizona, New Mexico, Utah, Colorado, Wyoming, Montana, and North Dakota; "irrigation" includes water applied by irrigation systems for agriculture and horticulture. Note that the six states considered in this study are New Mexico, Utah, Colorado, Wyoming, Montana, and North Dakota that together comprise about 36 percent of the total water withdrawal for irrigation purposes from amongst these 12 states.

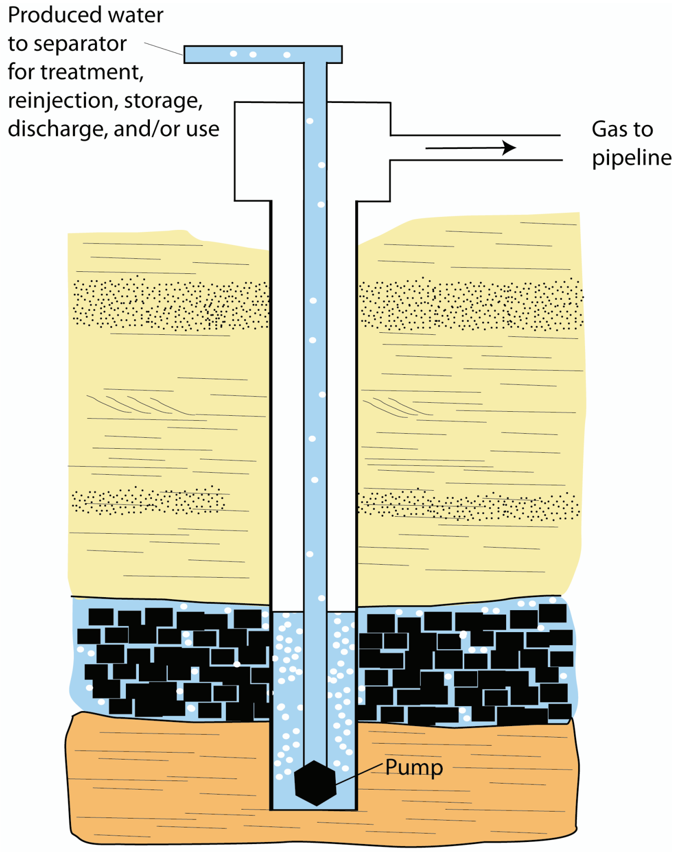

FIGURE 1.1 Illustration of the main features at a producing CBM well (not to scale). The black brick-like pattern represents a coal deposit lying between two sandstone units. The blue shading represents water that is present in the coal deposit. Methane gas (white dots and white shading) is adsorbed to the surfaces of the coal along cleats or fractures or is adsorbed to walls in the micropore structure of the coal matrix itself. Confinement of water in the coal by consolidated overlying and underlying sedimentary rock (sandstones in this figure) maintains the water in the coal under pressure, which in turn maintains the methane gas adsorbed to the coal. A submersible pump near the bottom of the well-bore cavity which penetrates the coal deposit pumps water from the coal. Pumping water reduces water pressure enough to allow methane to desorb from the coal surfaces and internal spaces and flow freely up the well bore. Water and methane flow through separate pipes to the surface. SOURCE: Adapted from Rice and Nuccio (2000).

professional football stadiums per day with water. While this volume of irrigation withdrawals contrasts to the approximately 42 billion gallons of CBM produced water generated in five western states in all of 2008 (see Chapter 2), water remains a vital resource and the effective, safe, and economical management of produced water from CBM wells is an important issue of consideration for government authorities, the general public, and industry.

NATIONAL CONTEXT FOR FUTURE CBM DEVELOPMENT AND PRODUCED WATER MANAGEMENT

Natural gas supplied about 24 percent of all domestic energy consumed by the United States' residential, commercial, industrial, and electrical power generation sectors in 2008 (EIA, 2009a). That same year the nation met about 87 percent of its domestic natural gas consumption with domestic resources, primarily methane, the main component of natural gas (EIA, 2009b). In addition to its domestic abundance, use of natural gas produces less carbon dioxide and significantly fewer criteria air pollutants[2] per unit of energy produced than any other fossil fuel. Natural gas has been described as a principal transition fuel to a less carbon-intensive U.S energy portfolio.

Projections suggest that unconventional natural gas may lead to an increase in the growth of the U.S. gas supply through 2030 (EIA, 2010a). CBM has become a significant part of total U.S. natural gas production over the last decade during which annual CBM production in the 48 conterminous United States increased from 1.3 trillion cubic feet (TCF) to 1.8 TCF, or just below 9.3 percent of total annual U.S. dry natural gas production (EIA, 2010b; see Figure 1.2).

Significant recoverable amounts of CBM occur in numerous sedimentary basins of the United States from the Appalachian and Black Warrior basins in the East to the Powder River, San Juan, Raton, Greater Green, Piceance, and Uinta basins of the West. Extensive CBM resources have also been mapped in Alaska (see Figure 1.3). CBM accumulations

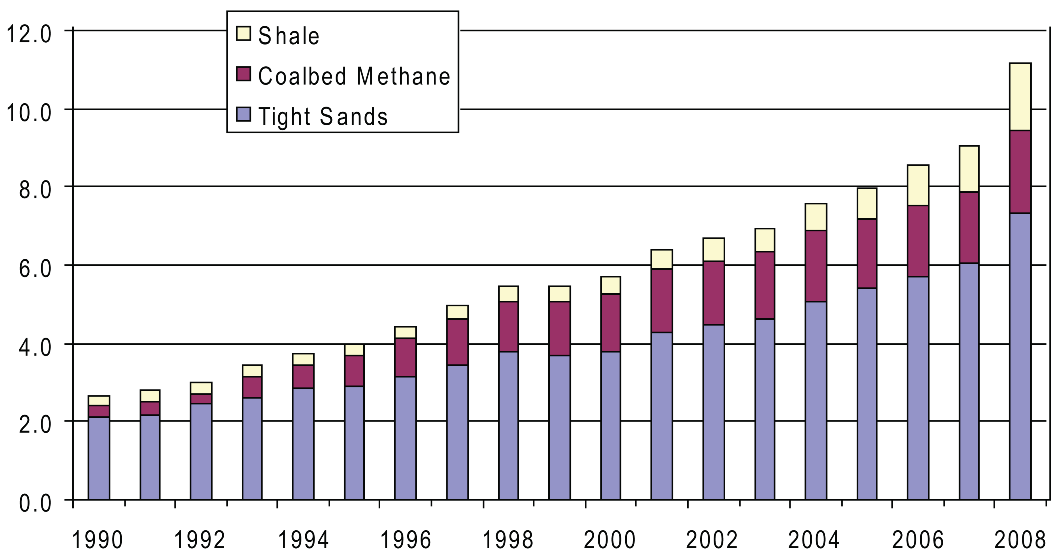

FIGURE 1.2 CBM has constituted a significant proportion of total unconventional U.S. gas production over the past two decades. This increase in production of methane gas from coalbeds reflects an increase in the number of CBM wells beginning in the early 1980s when development of CBM was stimulated by the Internal Revenue Service's Section 29 tax credit. The tax credit included incentives for development of new energy sources, including tax credits for unconventional fuels production. SOURCE: Adapted from EIA (2009c).

[2]Criteria pollutants are the only air pollutants with national air quality standards that define allowable concentrations of these substances in ambient air.

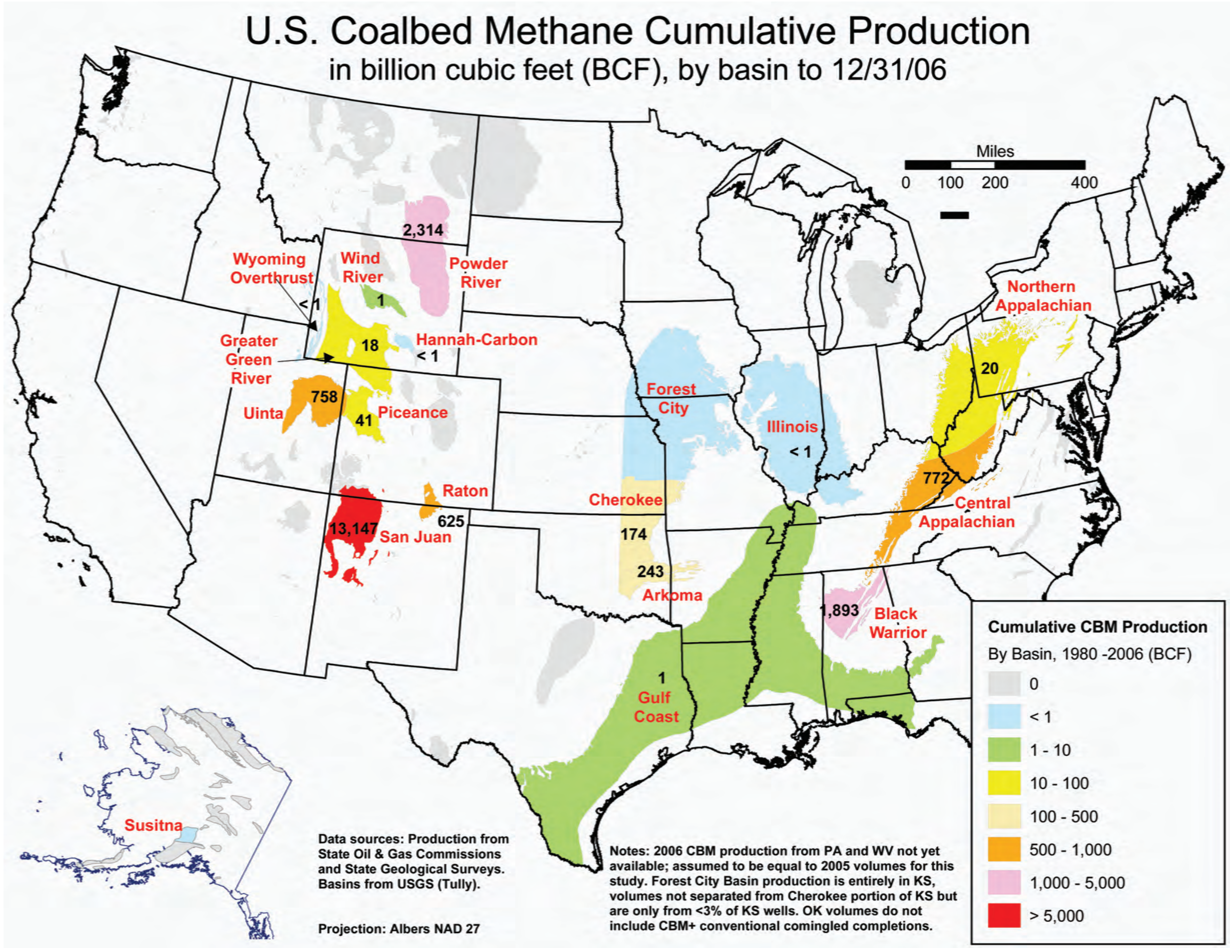

FIGURE 1.3 Sedimentary basins with CBM resources in the United States show the highest concentrations in the western United States. The Powder River, San Juan, Uinta, Piceance, and Raton basins comprise the largest currently known western U.S. recoverable resources and proved reserves (see Figure 1.4). SOURCE: EIA (2007).

vary within and among individual basins, depending on a basin's geological evolution, the grade of coal in the basin, and the hydrogeological setting of the coal deposits in the basin (see Chapter 2 for detail). Currently, the San Juan, Raton, and Powder River basins together comprise nearly 70 percent of all proven reserves in the nation (see Figure 1.4), and production from the Rocky Mountain States has far exceeded that of all other regions in the country combined over the past 10 years. The relative youth of the CBM industry in the West coupled with future demands for domestic energy and water resources indicate a continued need for effective, safe, and economical management of produced water from CBM activities.

REPORT OVERVIEW

The Energy Policy Act of 2005 (P.L. 109-58, Section 1811; see Appendix A) recognized the importance of CBM produced water management and directed the Bureau of Land Management (BLM) to enter into an agreement with the National Research Council

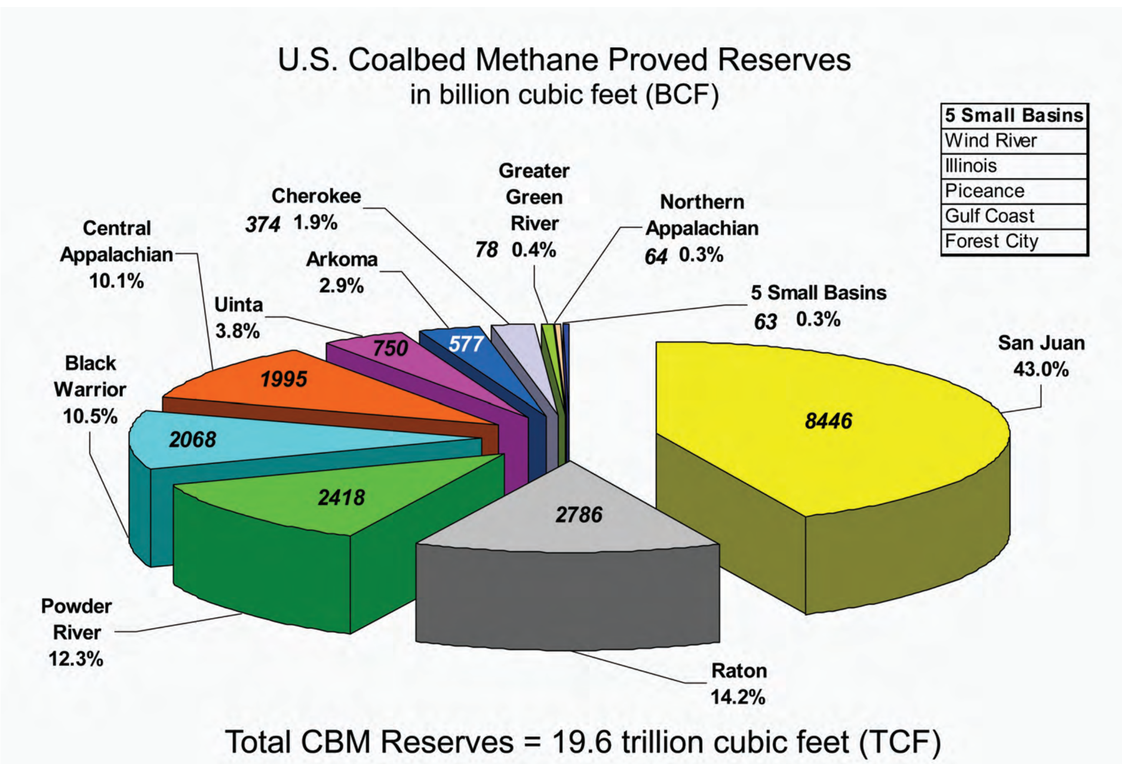

FIGURE 1.4 The San Juan and Raton basins of Colorado and New Mexico and the Powder River Basin of Wyoming and Montana contain the largest proportion of proved CBM reserves. SOURCE: EIA (2007).

(NRC) to examine the effects of CBM produced water on the environment in the western states of Colorado, Montana, New Mexico, Utah, Wyoming, and North Dakota. In its request, BLM asked the NRC (1) to review existing studies by federal agencies related to CBM produced water effects and management; (2) to generate an inventory of the federal and state data resources available for CBM produced water management; (3) to identify the major positive and negative effects of CBM produced water treatment, storage, disposal, and/or use on surface water and groundwater resources; (4) to review federal and state regulations for CBM produced water management; (5) to evaluate the effectiveness of current best management practices for the minimization of potential negative impacts to water resources; and (6) to discuss the costs for CBM produced water management. In response to this request, the committee of nine volunteer experts (see Appendix B) established by the NRC has developed this report, which is intended for Congress, BLM, and other federal, state, and tribal agencies, state organizations, the general public and public groups, and industry interested in increasing the effectiveness of CBM produced water management. This report organizes the discussion in the following way:

- The natural variables that affect produced water management, including the geological, hydrogeological, geochemical, and climatic factors specific to areas where western CBM production occurs (Chapter 2).
- The federal and state management and regulatory framework that has developed around CBM and produced water and determines what can and cannot be done to and with the produced water once it has emerged at the wellhead (Chapter 3).
- The range of management options, including water storage, treatment, disposal, and use, and positive and negative effects of CBM produced water that exist for the natural and constructed environments (Chapters 4 and 5).
- The technologies and costs to treat, store, dispose of, and/or use produced water (Chapter 6).

In its consideration of these factors, the committee has understood that technologies are available to treat water to *any* regulatory requirement or desired end use but that treatment costs and whether or not produced water is characterized as a waste or a potential beneficial use become decisive factors in which management options are employed, particularly in the arid West. These issues, as well as the report's conclusions and recommendations, are discussed in Chapter 7. Appendix C provides an overview of the presentations and meetings that served as some of the input to the committee's deliberations. Appendix D contains an inventory of the available federal and state data resources. Other references specific to individual chapters are cited at the close of each chapter.

CONCLUDING REMARKS

CBM produced water management is a complex issue for public and private sectors. Water is an increasingly valuable resource in the western states and elsewhere, and the beneficial uses for CBM produced water may become a larger part of the dialogue regarding produced water management. Although the committee was asked specifically to address the issue of produced water from CBM basins in the western United States, the conclusions and recommendations of this report may have relevance to ongoing activities in other CBM basins in the nation and to produced water and water use issues, more broadly, associated with both renewable and fossil energy resource development.

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CHAPTER TWO

Coalbed Methane Produced Water in Western U.S. Basins: Hydrogeological and Geochemical Foundations

A fundamental challenge regarding management of coalbed methane (CBM) produced water is determining to what degree surface water and groundwater resources may be depleted, supplemented, degraded, or enhanced and over what time periods as consequences of CBM extraction and management of produced water. To understand these consequences this chapter reviews the features of western CBM basins including (1) the hydrogeological characteristics of the basins; (2) the nature of connections between water in methane-bearing coal deposits and surface water and groundwater systems in the basins; and (3) the chemistry and age of the waters in the coalbeds.

The chapter focuses primarily on two basins—the San Juan Basin in Colorado and New Mexico and the Powder River Basin in Wyoming and Montana. These basins capture and contrast the currently known range of CBM produced water quality and quantity and produced water management approaches throughout the western CBM basins. The Uinta, Piceance, and Raton basins of Utah, Colorado, and New Mexico are also briefly discussed (see Figure 2.1). At present, no CBM production occurs in North Dakota.

HYDROGEOLOGICAL FOUNDATIONS

Origins of CBM and Associated Water

Coal is formed from plant matter (organic material) that has undergone burial, consolidation, and heating over millions of years under younger sediments. In the western United States, the wetland areas that provided the organic material for present-day coal basins existed between about 145 million and 56 million years ago. The plant matter formed either within alluvial systems of streams, lakes, and peat swamps, all of non-marine origin (northern Rocky Mountain area of the United States), or behind barrier islands and in back bays, lagoons, and deltas along the midcontinental seaway with waters of marine or

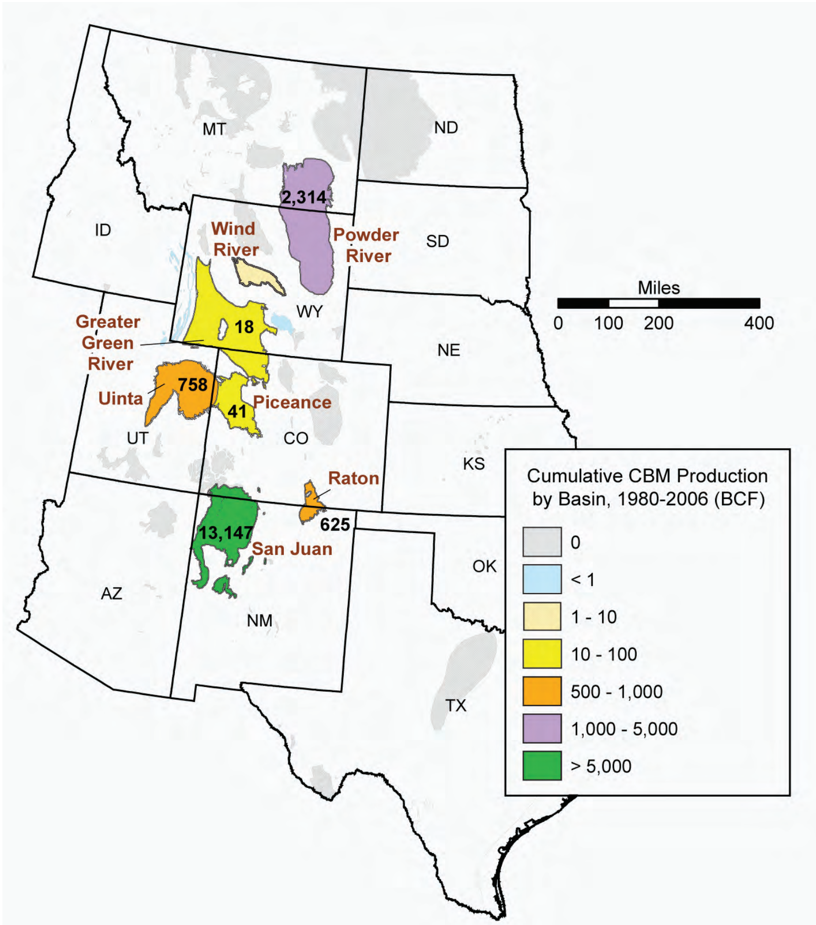


FIGURE 2.1 Map of western CBM basins within the six states that are the subject of this study. Only those basins with cumulative production to date greater than 40 billion cubic feet (BCF) are included in the discussion in this report. SOURCE: Adapted from EIA (2007).

brackish origin (southern reaches of the Rocky Mountains; see Figure 2.2). Because of the naturally discontinuous distribution of these wetland settings and the tectonic processes that affected buried coals during and after their formation, most of the coal deposits now in these western basins, although regionally pervasive, are also discontinuous. The coal deposits occur as seams or beds that are often distributed as discrete "lenses" or layers that pinch out, terminate, or branch (see descriptions of individual basins below). Discontinuities within these coalbeds or seams (hereafter referred to as "coalbeds") are important in that they affect the way in which water in the coalbeds and surrounding sedimentary formations migrates and is replenished.

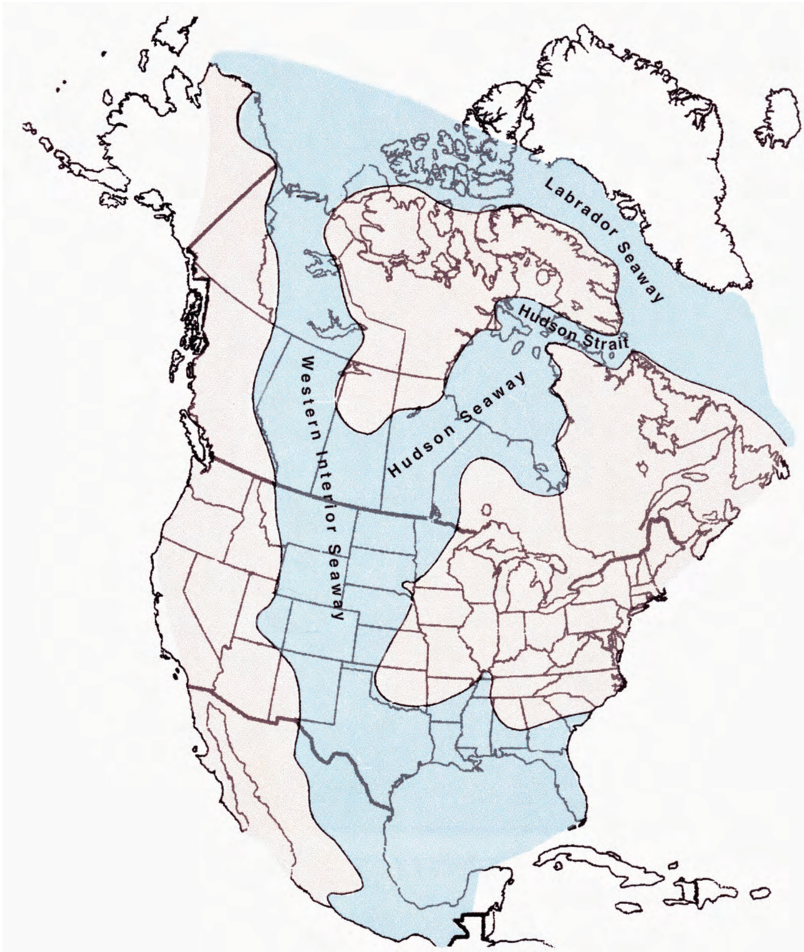


FIGURE 2.2 Illustration of the Cretaceous interior seaways, including the Western, Hudson, and Labrador seaways. The Cretaceous Period lasted from about 145 million to 65 million years ago. Coal-bearing basins in the western United States that are the subject of this report formed from organic-rich sediments (plant material) deposited in and along the wetlands of the Western Interior Seaway. The organic-rich sediments were deposited through Cretaceous and Paleocene (ca. 65 million to 56 million years ago) times during the rise and fall of intercontinental sea levels. SOURCE: W.A. Cobban and K.C. McKinney, USGS. Available at esp.cr.usgs.gov/research/fossils/ammonites.html.

Coalbeds can serve as aquifers or subsurface rock layers that are sufficiently permeable[1] to conduct groundwater and can provide sufficient water for human use. Other less permeable materials (e.g., siltstones, shales, clays) above and below the coal seams—sometimes

[1]A permeable geological material, or a material's "permeability," refers to its ability to transmit fluids and is generally associated with the degree of connectivity between pores in the material. A higher degree of pore connectivity would indicate higher permeability or ability of the material to transmit fluids.

called "aquitards"[2]—can inhibit upward or downward water flow from coalbeds. This inhibited flow essentially causes a water-saturated coalbed to be "confined" with respect to contained water. When water in a confined coalbed connects to the water table at an elevation above the elevation of the coal seam, the water in the coalbed may become overpressured with respect to the pressure exerted by a static column of water in the overlying rock (termed "hydrostatic pressure" or "hydrostatic head"). When a well is placed in a confined coal seam, the water level will rise to an elevation above the seam.

Because of the discontinuous nature of coalbeds, not all groundwater flow in coal-bearing basins can be described by simple hydrogeological models. These models usually describe water as moving from higher elevation "recharge" areas into lower elevation discharge areas from which the water may flow out as streams and springs. Groundwater "recharge" is a process by which water moves downward from the surface to groundwater and can occur naturally (e.g., rainwater percolation) or through artificial (human-induced) means. In some basins where natural recharge areas are located far from downgradient portions of a coalbed or other aquifers, replenishment of these aquifers by infiltrating precipitation may not occur within human lifetimes or even thousands to millions of years when water is removed from the aquifer. In essence this "old" or "fossil" water in a coalbed aquifer can be considered a "nonrenewable" resource once removed from the coalbed. The "age" of the water, or its residence time in the coalbed, thus also indicates the degree to which the CBM water is connected to surface water and shallow groundwater. "Old" water would suggest slow or inhibited connections to surface water or shallow groundwater that otherwise might serve as a source of "new" water to a coalbed.

Determining the connections between coalbeds and surrounding aquifers (hydraulic connections) and the renewability of the water resource in the coalbed is important to understanding the consequences of water removal from the coalbed during CBM production (described in detail later in the chapter). The age of the water in coalbeds from which CBM is being extracted thus can become an important factor in determining how produced water is managed. The next section outlines the development of methane and associated water in coalbeds. Subsequently, geological and hydrogeological characteristics of each basin are briefly described because of the role they play in determining both the volume and quality of water produced during CBM extraction.

[2]An "aquitard" is a confining bed or geologic material that retards but does not prevent the flow of water to or from an adjacent aquifer, does not easily yield water to wells or springs, and may serve as a storage unit for groundwater. An "aquiclude" is a body of relatively impermeable geologic material that can absorb water slowly but does not transmit it rapidly enough to supply a well or spring (Bates and Jackson, 1987).

Production of Methane and Water from Coalbeds

Methane associated with buried coalbeds is originally formed from one of two processes: thermogenesis or microbial methanogenesis. Thermogenesis involves the degradation of organic matter by temperatures usually greater than 120° C (248° F) associated with pressure from burial at depths greater than about 1,000 feet. The San Juan Basin contains coals with themogenic methane. Microbial methanogenesis is the decay of organic matter through microbial activity at relatively shallower depths and lower temperatures than those related to thermogenesis; the Powder River Basin coals contain methane generated in this way. In addition to genesis of methane during compaction and heating of organic material, coals develop systematic fractures or "cleats," roughly analogous to cleavage planes in minerals (Riese et al., 2005). The presence of water in the coalbeds keeps the methane adsorbed on the surfaces of the coal and within the cleats and adsorbed to walls in the micropore structure of the coal matrix (see Figure 1.1). Water in the coalbeds may derive from (1) original water ("connate" water) associated with freshwater or marine settings in which the organic material was originally deposited, and/or (2) water (e.g., rainfall) that later percolated from the surface through to the coals as they were progressively buried.

To extract methane adsorbed to the coal, water must be pumped out of coal seams to lower the water pressure (head) and allow the methane to desorb, coalesce, and bubble into the pumped water, analogous to the formation of bubbles of carbon dioxide in a bottle of carbonated beverage when the cap is removed (see Figure 1.1). The amount of water that must be removed from the coalbeds in order to release methane depends on the original water pressure in the coal, the physical capacity of the coal to hold and release water, and the extent to which coals may be hydraulically connected to adjacent geological formations. Water production records show that the volume of water pumped from individual CBM wells generally decreases exponentially with time, with a corresponding increase in the rate of methane production (see Figure 2.3). In many cases, water pumping may discontinue within 10 to 20 years of initial pumping, while methane production may continue.

In contrast to conventional oil and gas fields where produced water is sometimes reinjected into the producing formation to enhance oil and gas recovery, CBM produced water is not returned to the coal seams from which it was extracted because doing so would hinder additional methane recovery. Thus, other options are considered with respect to storage, disposal, or use of the CBM produced water.

The generalized trend shown in Figure 2.3 for water and methane production related to CBM extraction is useful for discussion of long-term predictions for water and gas volumes from a particular basin. However, the volume of water produced per year, the ratio of water to gas extracted from a well, and lifetime water production within and between the western CBM basins do not follow a common trend. Hydrogeological properties and operational practices affect the volume of water produced. For example, the rate at which

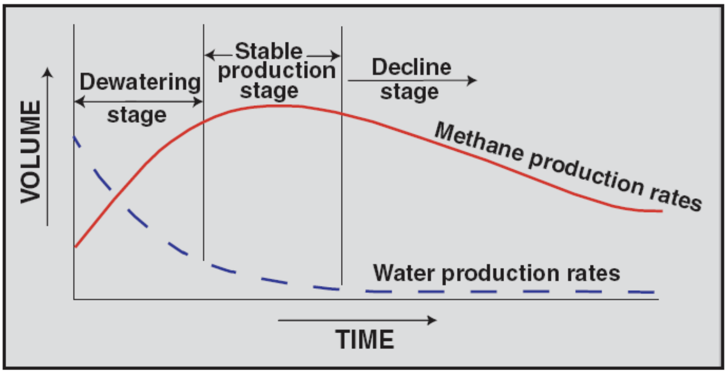


FIGURE 2.3 Schematic production curves for typical CBM wells show that operator-controlled water production rates decrease exponentially over time while methane production increases before moving into a stage of decline. Water production is a function of initial, operator-controlled pumping rates that aim to reduce pressure and stimulate flow of water and gas to the well. Once gas flow has been achieved, over time, the operator will gradually reduce the water production rate until the gas production rate is maximized. SOURCE: Nuccio (2000).

pumped water enters wells during production depends on the natural hydraulic properties and water-filled porosity of the coal seam containing the methane and the operator-controlled water-pumping rate. Shallow, weakly-consolidated coalbeds may have extensive internal fractures and interconnection of fractures that produce a porous and permeable formation capable of releasing large amounts of water during methane production (e.g., the Powder River Basin). In other areas where the methane-bearing coalbeds lie at much greater depths, the amount of water that must be pumped from the coal and the rate at which that water can be pumped to facilitate the release of methane are often limited by the effective water-filled porosity and permeability of the coal (e.g., the San Juan Basin). The limited interconnectivity between fractures and cleats in these deeper coals often requires use of hydraulic fracturing to stimulate release of the methane (Box 2.1; see also Chapter 5).

CBM production and associated produced water volumes are also a function of economic conditions. Generally, if the price of natural gas goes below a certain price point, the CBM operator will begin to "shut in" (cease to produce from) wells, which will reduce the quantity of produced water generated by the industry. When natural gas prices are above a certain level, CBM operators will generally increase production to generate more income and profit. The total volume of CBM produced water generated by a CBM operator will thus vary as a result. Other factors such as contract deliverables, reservoir management requirements, and reservoir energy may also affect the decision to shut in a well or keep it in production.

BOX 2.1
Hydraulic Fracturing

Hydraulic fracturing is a technique used in many oil and gas production settings to help release oil or gas from the geological formation and allow the hydrocarbon to flow more freely and consistently to the well bore. The technique injects fluids and sand under pressure into the formation of interest to open and stimulate the growth of new fractures, thereby increasing the number of pathways through which oil or gas can reach the well. Among the CBM basins examined in this study, hydraulic fracturing is used to enhance the flow of methane gas in the San Juan, Raton, Piceance, and Uinta basins. Hydraulic fracturing is used very infrequently in CBM operations of the Powder River Basin due to the high natural permeability of the shallow, methane-bearing coal seams. The standard industry practice for oil and gas operators to fracture a formation hydraulically is to fill the space between the outside of the steel casing of the well pipe and drill hole with cement along some or all of the well bore to the top of the target rock unit from which oil or gas (including methane from coalbeds) is going to be recovered. Holes or perforations are then blasted through the well casing opposite the target rock formation (for CBM production, the target is the coal seam). Fracturing fluids, if used, are pumped under high pressure through these holes into the target formation and are then pumped, together with the oil and gas and/or any produced water, back to the surface for recovery and disposal. In the Montana portion of the Powder River Basin, water, rather than other fluids, may be injected into CBM wells by some operators to improve conductivity around the well bore. The well casing and encasing concrete in a CBM well are designed to maximize recovery of all types of fluids from the target formation and to minimize loss of fluid, whether hydraulic fracture fluid, oil, gas, or water, to other geological formations along any part of the well bore.

Western CBM Basins

This section provides an overview of the variations in regional geological and hydrogeological histories for the western CBM basins. These variations have direct bearing on the subsurface depth from which methane is extracted and the volume and chemistry of associated produced water. In discussing the chemistry of CBM produced water, the committee sometimes uses the qualifying word "relatively" to denote differences in the total dissolved solids (TDS)[3], salinities, and sodicities of CBM produced waters as they vary across the western basins. For example, CBM produced water from the Powder River Basin is sometimes described as "relatively fresh," whereas CBM produced water from the San Juan Basin may be described as having "relatively high salinity." The section on "Geochemi-

[3]TDS (total dissolved solids) is an expression for the combined concentration of all inorganic and organic substances contained in a liquid which are present in a molecular, ionized or micro-granular suspended form, and which will pass through a sieve opening of 2 micrometers (Water Systems Council, 2007).

cal Foundations" later in this chapter provides the background for the use of these terms throughout the report.

Powder River Basin

The Powder River Basin of Wyoming and Montana covers approximately 25,800 square miles (see Figure 2.4). CBM in the basin is derived from coals in the Tongue River and

(a)

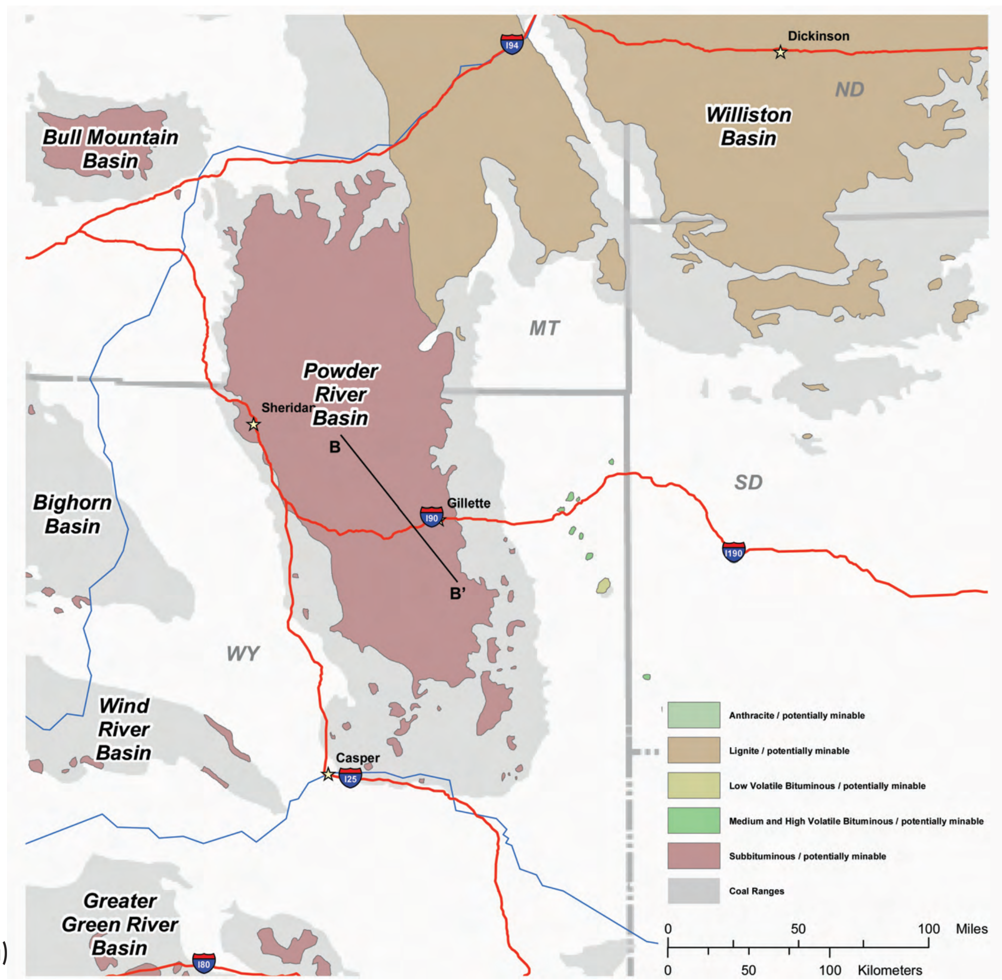
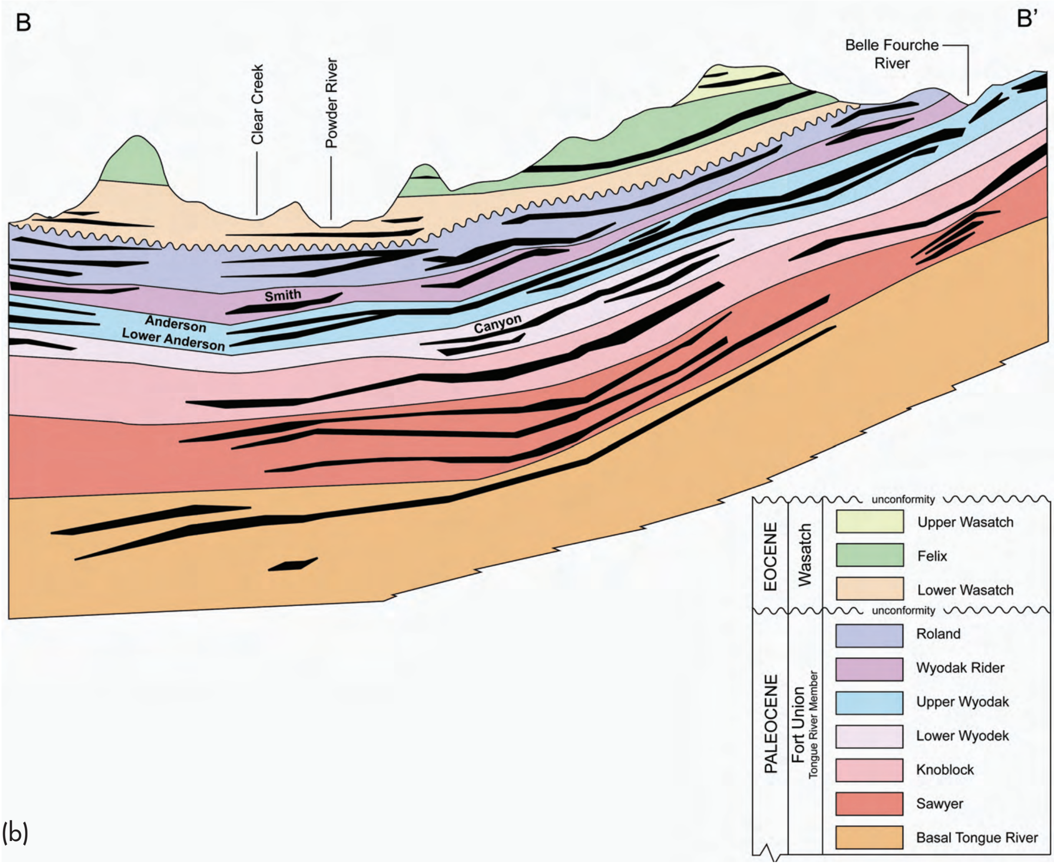


FIGURE 2.4 (a) Powder River Basin of northeastern Wyoming and southeastern Montana. Major drainages flow north or east into the Missouri river system. Location of cross-section B-B′ in Figure 2.4b is shown within the purple-brown shading that indicates coal of subbituminous grade. (b) Northwest-southeast



(b)

geological cross section through the basin depicts a major coal-bearing and CBM-producing rock unit, the Fort Union Formation, and the overlying Wasatch Formation. Although oil and gas production began in the Powder River Basin in the 1920s, the first CBM well was not drilled there until the late 1980s (in the Wyoming portion of the basin). By the end of 2008, approximately 18,000 CBM wells were extracting methane from the Tongue River and Lebo Shale members of the Fort Union Formation, mostly at shallow depths ranging from approximately 450 to 4,500 feet (USGS, 2005). Wells shallower than 450 feet have produced methane from coalbeds in some localized areas. The Wyodak coal zone, including the Lower and Upper Wyodak and Wyodak Rider zones, contains the Canyon, Anderson, Smith, and Big George coals, which are CBM production targets. Vertical and lateral correlations in the Fort Union Formation show successive splitting of thick coal beds resulting in overlapping coal zones (Flores et al., 2010). This effect has played a role in the use of slightly different nomenclature to identify coal horizons in the basin. For example, the Anderson coal is sometimes referred to as the Wyodak coal; in the northwestern part of the basin and in Montana, the Anderson and Canyon coals are interleaved with the Dietz coal (sometimes referred to as the "Anderson-Dietz coal"). The Smith and Big George coals are not easily differentiated in every part of the basin and are sometimes referred to as the Smith/Big George coal, or as in the case of this cross section, only as the Smith coal. Elsewhere in the basin, the Big George coal occurs in the same part of the Wyodak Rider zone and is identified as such (Copeland and Ewald, 2008). The Lebo Shale Member is not depicted on this cross section but lies below the Tongue River Member. SOURCES: (a) ALL Consulting (2003); (b) Adapted from Copeland and Ewald (2008).

Lebo Shale members of the Fort Union Formation, which formed about 65 million to 56 million years ago (Paleocene time). The Fort Union Formation, a heterogeneous geological unit of sandstone, shale, and coal deposits, is overlain by the Wasatch Formation in many locations. These formations outcrop extensively around the east-central margin of the Powder River Basin near Gillette, Wyoming, and around the west central margin of the basin near Sheridan, Wyoming. Open-pit and strip-mining commercial coal operations are common in the outcrop areas.

Thickness of individual coalbeds in the Fort Union Formation ranges from a few inches to over 200 feet, with an average thickness of 25 feet. The Fort Union Formation originally was deposited on the margins of an ancient interior seaway as part of river (freshwater, fluvial) systems with braided, meandering, and dissected streams in the center of the basin and alluvial plains along the basin margins (USGS, 1999; Copeland and Ewald, 2008). The irregular spatial and vertical distributions of coalbeds (laterally and vertically discontinuous) reflect shifts of these fluvial and alluvial systems through time. The Tongue River Member of the Forth Union Formation contains thick, laterally extensive coalbeds that vary unpredictably in thickness and geometry, terminating and merging abruptly. The Tongue River Member, including the Wyodak coal zone[4] and the Canyon and Anderson coals within this zone, contains most of the recoverable CBM in the Wyoming portion of the Powder River Basin (Figure 2.4b; Copeland and Ewald, 2008).

In the eastern part of the basin, regional groundwater flow moves from the south and east toward the northwest and into the central part of the basin (Daddow, 1986; Martin et al., 1988). In the southeastern part of the basin, regional groundwater flow is to the north, although local flow often varies from this overall pattern (BLM, 2003; USGS, 2005). The generally northward regional groundwater flow in the basin moves slowly because of pinching out of sandstone units, which are the principal water-conducting deposits contributing to groundwater flow. Water in sandstone aquifers associated with the coalbeds can be hydraulically confined, particularly in deeper, isolated beds far from recharge areas. Individual coalbeds in the Wasatch, Fort Union, and Lance formations (e.g., the Anderson coal) can also constitute important aquifers.

The Wyodak and Wyodak Rider coal zone of the Fort Union Formation is the most hydrologically continuous unit in the Powder River Basin and, together with its related coalbeds (the Anderson, Canyon, Big George, and Smith coals; Figure 2.4b), constitutes a regional aquifer. Limited recharge to the Wyodak and Wyodak Rider coal zone occurs at outcrops along the eastern margin of the Powder River Basin (e.g., Daddow, 1986). Recharge water flows downgradient within the coalbeds that outcrop at the surface. These

[4] A "coal zone," according to Copeland and Ewald (2008), is a stratigraphic interval containing a suite of coalbeds that vary in thickness, have stratigraphic proximity to one another, and split apart or merge from a single coalbed.

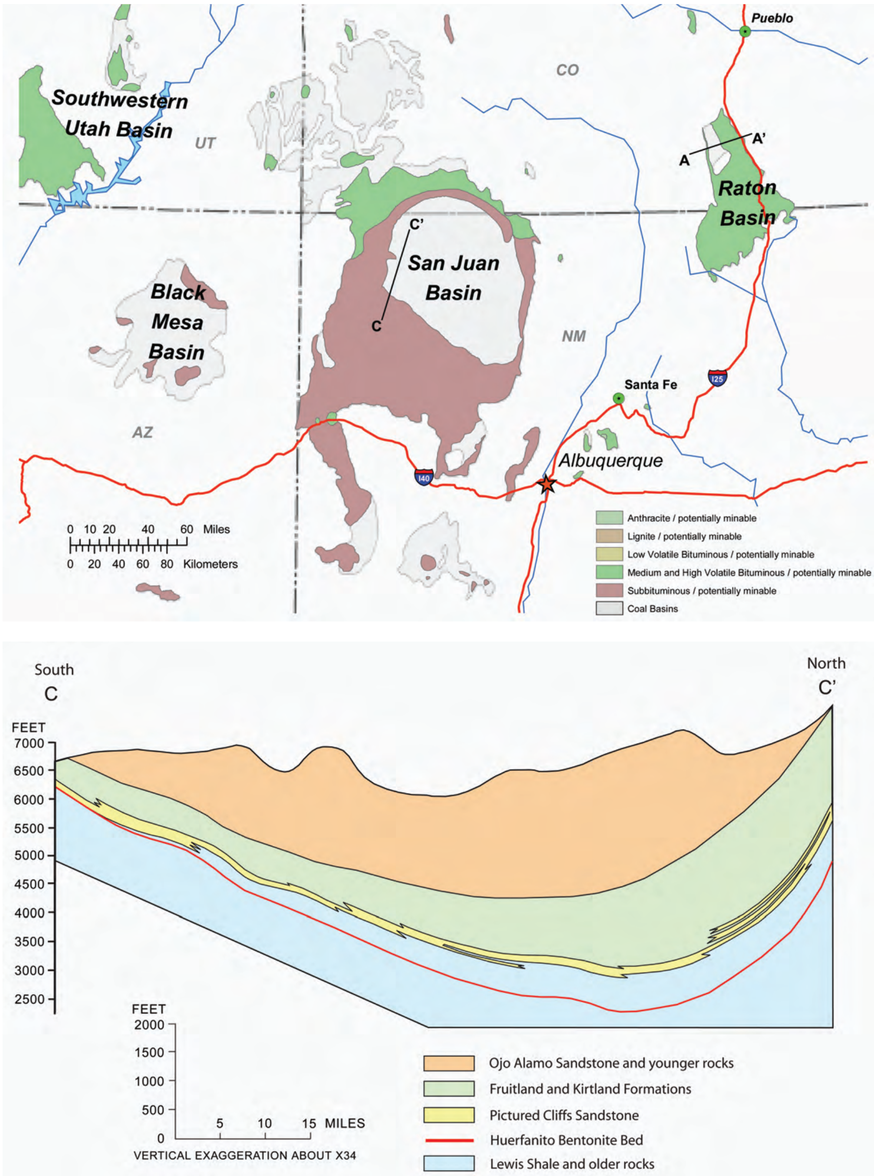
coalbeds then act as independent isolated aquifers. Flow into or out of the coalbeds along fault and fracture lines takes place to a limited extent (Frost et al., 2010).

Because the origin of the coals in the Wyodak and Wyodak Rider coal zone was in a freshwater setting, as opposed to a marine setting—which was the case for the coal deposits of the San Juan, Raton, Uinta, and Piceance basins—the connate waters associated with the Powder River coals were probably fresher from the outset compared to the connate coalbed waters in the other basins. In cases where the Powder River Basin coals are also connected hydraulically to natural recharge areas, the higher relative permeability of the coals would facilitate flow and contribute further to water chemistry in the coals having relatively few dissolved solids compared to water in coalbeds of other western CBM basins (see section on "Geochemical Foundations" later in this chapter). As a result of some combination of these natural circumstances, relatively fresh connate water and/or higher relative permeability, produced water from the Powder River Basin coalbeds is generally less saline than waters produced from other western CBM basins. The low TDS content and low salinity allow management of the CBM produced water either through direct discharge to ephemeral and perennial streams (either with or without treatment) or storage in surface impoundments (see later in chapter for water chemistry and Chapter 4 for details of water management practices in the basin). The degree to which water in the coals of the Wyodak and Wyodak Rider coal zones represents original ("old" or "fossil") connate water and/or younger water that percolated into the coal from surface recharge areas is not well constrained with geologic, geophysical, geochemical, or hydrologic data.

San Juan Basin

The San Juan Basin covers about 7,500 square miles in the Four Corners region of the adjoining states Utah, Colorado, Arizona, and New Mexico (Figure 2.5). The basin strikes west-northwest to east-southeast and is asymmetrical in shape, with the deepest and thickest sedimentary rocks located in the north-central portion of the basin. The major coal-bearing and methane-producing unit is the Cretaceous Fruitland Formation, underlain by the Pictured Cliffs Sandstone. The layered and discontinuous Fruitland coals have three-dimensional complexity, reflecting the original complexity of the back-barrier lagoonal wetland ecosystems from which they originated (Snyder et al., 2003; Riese et al., 2005).

Production of CBM from the San Juan Basin occurs at depths ranging from 550 to 4,000 feet in three distinct and geographically discrete hydraulic pressure and permeability zones: (1) a central, high hydraulic head, high-permeability "fairway" (primarily in the gray shading of the basin in Figure 2.5a); (2) a northern, high hydraulic head, low-permeability area (primarily in the green and purple-brown shading of the northern part of the basin in Figure 2.5a); and (3) a southern, low hydraulic head, low-permeability area (primarily in the purple-brown shading of the southern part of the basin in Figure 2.5a). Although the



(a)

(b)

FIGURE 2.5 (a) The San Juan Basin of northeastern New Mexico and southwestern Colorado. The green, purple-brown, and gray shading indicates coal of bituminous through subbituminous grade. Location of cross-section C-C′ in Figure 2.5b is identified. (b) A south-north cross section through the San Juan Basin shows the asymmetry of the basin and its major coal-bearing and methane-producing rock unit, the Fruitland Formation, underlain by the Pictured Cliffs Sandstone and overlain by the Ojo Alamo Sandstone. Although oil and gas production began in the San Juan Basin in the 1920s, CBM development did not flourish until the mid-1980s. By the end of 2008, more than 7,000 CBM wells were active, extracting methane from coal deposits primarily within the Fruitland Formation at depths up to 4,000 feet below the surface. SOURCES: (a) ALL Consulting (2003); (b) Adapted from Fassett (2008).

hydraulic head in two of these zones is considered "high" (with respect to the hydrostatic water column), the reservoir water volumes are relatively low (with respect to the Powder River Basin), while the gas volumes remain relatively high (EPA, 2004; see also Table 2.1). Given this condition and the relatively high salt content of the produced water (refer to section on "Geochemical Foundations" later in this chapter), CBM producers in the San Juan Basin put a large majority of produced water from the coalbeds into temporary storage in above-ground storage tanks for later reinjection into formations below the coal.

Raton Basin

The Raton Basin of Colorado and New Mexico covers approximately 3,100 square miles (see Figure 2.5a) and is an elongate asymmetric syncline approximately 80 miles long (north-south direction) and 50 miles wide (east-west direction) (see Figure 2.6). Coal

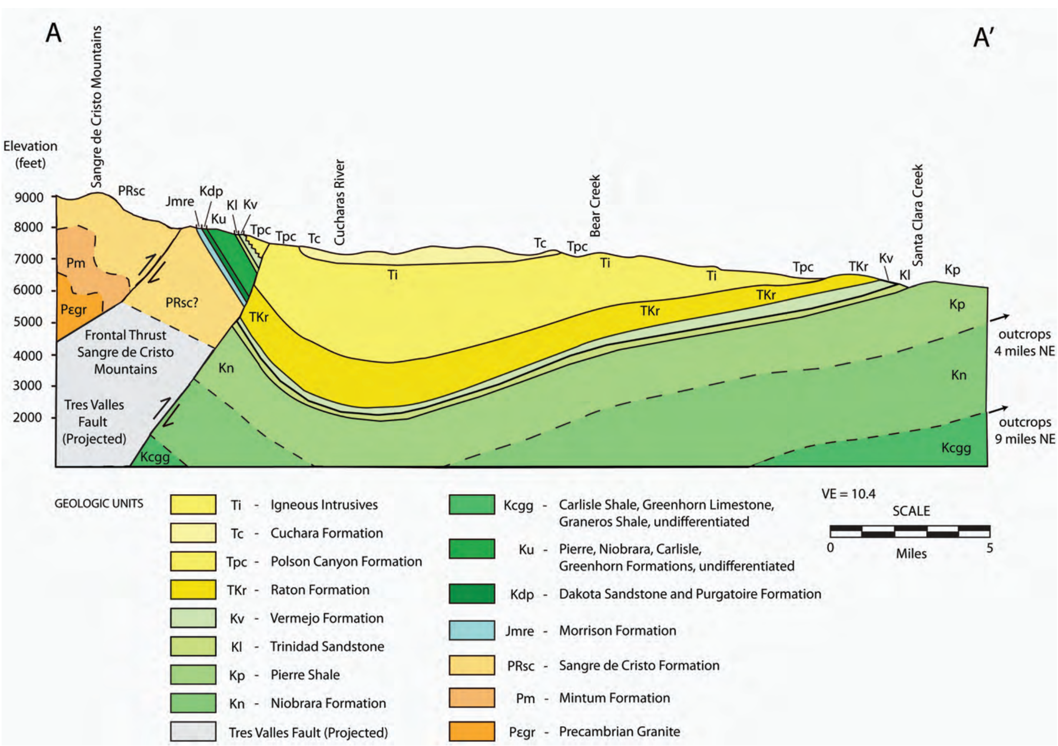


FIGURE 2.6 West-to-east cross section (see location A–A′ in Figure 2.5a) through the Raton Basin shows an asymmetry similar to the San Juan Basin. The primary coal-bearing and CBM-producing units are the Vermejo and Raton formations. Depth to the methane-bearing Vermejo Formation coal zone is about 2,400 feet (Johnson and Finn, 2001). SOURCE: Adapted from Stevens et al. (1992). Reproduced by permission of the Gas Technology Institute.

and associated methane in the Raton Basin derive from the late Cretaceous Vermejo and Raton formations, which overlie the Trinidad Sandstone, a basinwide marine sandstone (Figure 2.6). The Vermejo Formation was deposited as a collection of channel, lagoon, coastal swamp and delta plain deposits and the Raton Formation was deposited on a continental alluvial plain as a collection of channel, overbank, and swamp deposits. Numerous thin coalbeds in the Vermejo and Raton formations cannot be correlated over more than a few miles (Haley, 2004). Magmatic intrusions into the sediments also disrupt the sedimentary rock succession, including the coals. As with the other CBM basins in the West, water quality as a function of TDS varies widely across the basin, ranging from 900 to 3,500 ppm TDS on the western side of the basin, to 15,000 to 30,000 ppm TDS closer to the eastern outcrop.

Piceance and Uinta Basins

The Piceance Basin is located in the northwest corner of Colorado (see Figure 2.7a). Commercially recoverable amounts of methane occur in the Upper Cretaceous Mesaverde Group, which covers about 7,225 square miles of the basin. The Mesaverde Group ranges in thickness from about 2,000 feet on the west to about 6,500 feet on the east side of the basin (Johnson, 1989). Depth to the methane-bearing Cameo-Wheeler-Fairfield coal zone is about 6,000 feet, making methane extraction somewhat more technically challenging than in other areas where the formations are shallower (Figure 2.7b). In general, potable water wells in the Piceance Basin extend a few hundred feet below the ground surface, vertically a mile from the methane-producing zone. Below a depth of about 200 feet, the salinity of produced water can be as much as half the salt concentration of seawater (EPA, 2004).

The Uinta Basin of east-central Utah and northwestern Colorado covers approximately 14,400 square miles and is similar in its composition and history to the Piceance Basin. The Uinta Basin is separated structurally from the Piceance Basin near the Utah and Colorado border (Figure 2.7a). Similar to the Piceance Basin, coal occurs in the Cretaceous Mancos Shale and the overlying Mesaverde Group at depths of about 1,000 to over 7,000 feet below ground surface (Garrison et al., 1997). Coals from which CBM can be commercially recovered occur 4,200 to 4,400 feet below the surface (Gloyn and Sommer, 1993). Coalbeds are present within Cretaceous sedimentary rocks throughout much of the Uinta Basin. However, CBM exploration has targeted coalbeds in a sandstone member within the Mancos Shale and coalbeds in the Mesaverde Group. The sandstone in the Mancos shale was deposited in a fluvial-deltaic environment. The coalbeds in the Mesaverde Group consist of coal interbedded with sandstone and a combination of shale and siltstone. As with the Piceance Basin, water quality associated with the Uinta Basin CBM can be very saline, and salinity of produced water may be as much as that of seawater.

(a)

(b)

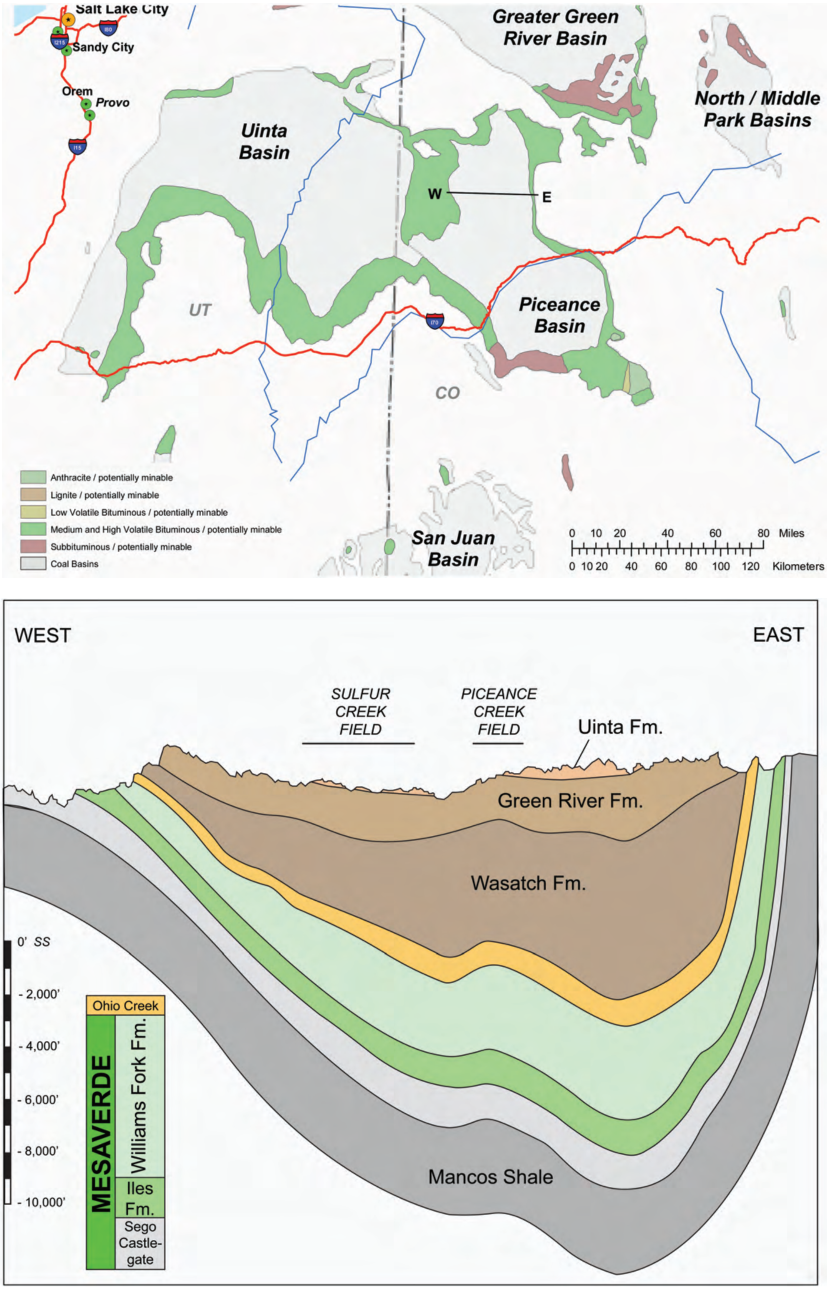


FIGURE 2.7 (a) Geological map of the Piceance and Uinta basins. Cross-section for the Piceance Basin in Figure 2.8b is identified. (b) Generalized west-east geological cross section across the Piceance Basin of Colorado. The CBM is found in the Mesaverde Group. Fm = Formation. SOURCES: (a) ALL Consulting (2003); (b) RMAG Special Publication by Yurewicz, D.A., et al. Copyright 2003 by Rocky Mountain Association of Geologists. Reproduced with permission of Rocky Mountain Association of Geologists.

Variations in CBM Produced Water Volumes

The Powder River and San Juan basins have seen the most CBM development, followed by the Raton Basin, as illustrated by the number of wells operating in each basin (Table 2.1). The Piceance and Uinta basins have seen significantly less CBM development. Water and gas production curves from the Powder River, San Juan, Piceance, and Raton basins illustrate variations in CBM produced water volumes. These variations illustrate the difficulty in predicting water and gas production volumes for a basin through time due to interplay of natural hydrogeological characteristics of the basins, the number of existing and new wells, and operator pumping rates.

The greatest volume of water production occurs in the Powder River Basin (Figure 2.8a, b), where the methane-producing coalbeds are water filled, relatively porous and permeable,

TABLE 2.1 Water and gas production information for CBM in the Powder River, San Juan, and Raton Basins in 2008 (data for the Piceance and Uinta basins are from 2006 and 2000, respectively)

Basin	State	Start Date	Depth (feet) to Coalbeds for Methane Production	Estimated Water Production (million barrels)	Estimated Gas Production (million MCF)	Approx. No. of CBM Wells	Estimated Water-to-Gas Ratio (barrels/MCF)
Powder River	WY, MT	1989, 1998	450–4,500	718	435.2	18,000	1.65
San Juan	CO, NM	1985	Up to 4,000	46	1,210.5	7,500	0.038
Raton	CO, NM	Early 1980s	Up to 2,400	131	147.2	3,400	0.89
Piceance	CO	1989	Up to 6,000	0.30	0.25	110	1.2[a]
Uinta	UT	Early 1990s	4,200–4,400	31	73.8	1,255	0.42

[a]Relatively high water-to-gas ratio in 2006 does not reflect long-term CBM production trends in the Piceance Basin. Refer to Figure 2.8d.

SOURCES: Powder River Basin data adapted from Meredith et al. (2010); wogcc.state.wy.us (accessed March 5, 2010); and C.D. Frost, presentation to the committee, June 2, 2009. Raton Basin data adapted from Hemborg (1998); Topper (2009); and M. Fesmire, presentation to the committee, June 2, 2009. San Juan Basin data adapted from S.S. Papadopulos & Associates, Inc. (2006); Topper (2009); M. Fesmire, presentation to the committee, June 2, 2009; and D. Mankiewicz, presentation to the committee, June 2, 2009. Piceance Basin data adapted from S.S. Papadopulos & Associates, Inc. (2007), and Topper (2009). Uinta Basin data adapted from Rice and Nuccio (2000) and EPA (2004).

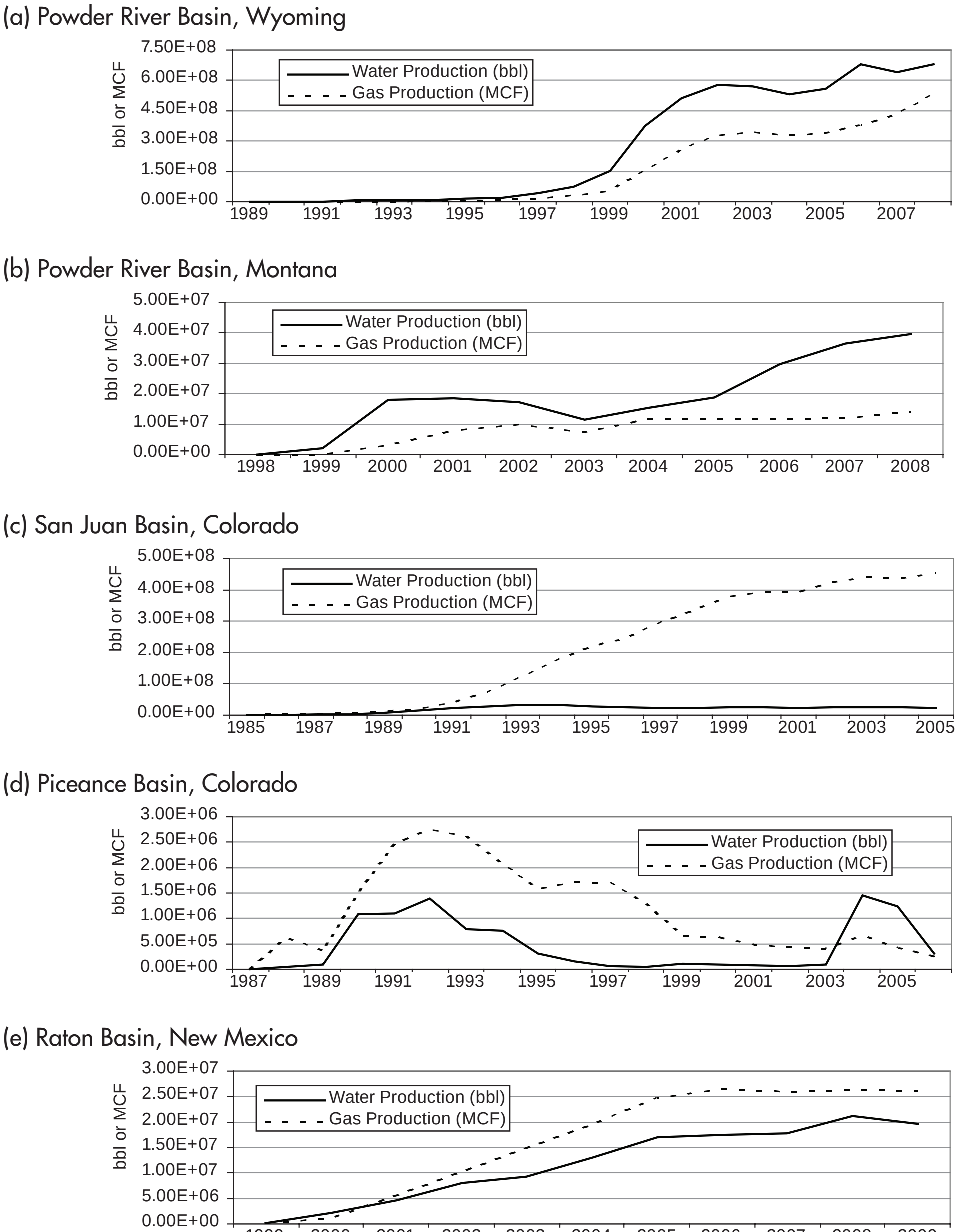


FIGURE 2.8 Annual water and gas production curves for CBM activities in the Powder River, San Juan, Piceance, and Raton Basins. "bbl" = barrel. SOURCES: Powder River Basin, Wyoming, data adapted from wogcc.state.wy.us/ (accessed March 5, 2010); Powder River Basin, Montana, data adapted from Meredith et al. (2010); San Juan Basin, Colorado, data adapted from S.S. Papadopulos & Associates, Inc. (2006); Piceance Basin, Colorado, data adapted from S.S. Papadopulos & Associates, Inc. (2007); and Raton Basin, New Mexico data adapted from octane.nmt.edu/gotech/Main.aspx (accessed June 21, 2010).

and located at relatively shallow depths compared to the other western CBM basins. In both the Wyoming and Montana portions of the basin, water and gas volumes have increased from the late 1990s until the present, as have the number of water- and CBM-producing wells, yielding an average water-to-gas ratio (in barrels of water produced per thousand cubic feet [MCF] of gas produced) greater than 1 (Table 2.1).[5] Attempts at methane extraction in one-sixth of the Powder River Basin fail because water-to-gas ratios are excessively high, compared to other parts of the basin (Table 2.1).[6]

CBM production in the San Juan Basin yields a much lower water-to-gas ratio than in the Powder River Basin (Figure 2.8c). Low ratios are typical of basins with deeper, less permeable coalbeds that have been producing methane for a longer period of time. A graph of production from the San Juan Basin shows a steady increase in gas production since the mid-1990s, while water production from the basin peaked in 1993 and has since followed a steady decline.

In an example from the Piceance Basin, which has the lowest CBM production levels of any of the western CBM basins, two spikes in water production are apparent (Figure 2.8d). The first peak in water production in late 1992 reflects the increase in pumping rates and number of wells as production began in the basin. The second is due to input of a large number of new wells in the 2003 to 2004 period and accounts for the relatively high water-to-gas ratio in 2006 (see Table 2.1).

Acknowledgment of these kinds of variations in water production from basin to basin and within a basin is important when considering CBM produced water management options. Any discussion of "average," "annual," or "total" water production values requires clarifying information, including the length of time over which CBM operations have been active in the basin, the total number of operating wells, the number of existing and new wells in a given part of a basin in a given year, how long those wells may be in operation, and the rate of pumping by the operator. Spacing of adjacent wells may also have an effect on how quickly or slowly water production proceeds in a CBM field (see Chapter 5). These types of data are not necessarily available in a single data repository for each state or basin but have to be compiled from numerous information sources (see Figure 2.8 and Table 2.1 for some of these data sources).

[5]A U.S. barrel (bbl) is equivalent to 42 gallons. One thousand MCF is equivalent to 1,000,000 cubic feet (see values in Table 2.1).

[6]D. Fischer, Wyoming Department of Environmental Quality, presentation to the committee, March 30, 2009.

CASE STUDIES: REGIONAL HYDROGEOLOGY AND HYDRAULICS OF THE SAN JUAN AND POWDER RIVER BASINS

San Juan Basin

Fine-grained rocks (shale) confine the Fruitland coal and sandstone aquifers in the San Juan Basin. These aquifers become unconfined at outcrops at the basin margins. The situation is similar for the coal-bearing units of the Raton Basin. Because the coal-bearing beds outcrop at the surface at elevations higher than where they occur in the interior of the basin and the coalbeds are confined, the coalbeds had been previously considered a case of a classic "confined aquifer" that recharges at the outcrops along basin margins. Regionally, this model would predict groundwater to move in a southerly direction, from topographically high recharge areas in the north to the central part of the basin and to the lower basin margins, where the groundwater would discharge.

However, data indicate that this classic confined aquifer model for the San Juan Basin is too simplistic to adequately describe the complex hydrological process that governs confined coalbed water recharge, drawdown, and discharge. Isotopic analyses, including iodine, chloride, carbon, oxygen, and hydrogen in groundwater of multiple geochemical systems, independently document that the residence time (age) of CBM water in the San Juan Basin is on the order of thousands to tens of millions of years (e.g., Phillips et al., 1986, 1989; Snyder et al., 2003; Riese et al., 2005; see Box 2.2). Within the uncertainties of isotopic analysis, these data indicate that meaningful recharge of groundwater to all coalbed aquifers with the exception of some of the peripheries of these basins, in close proximity to the outcrop areas, has not occurred within the scale of human time.

Recent data from multiple lines of geological, geochemical, geophysical, biological, and ecological investigation have further demonstrated that the last major recharge of water to the San Juan Basin coal systems occurred during Eocene time, approximately 35 million to 40 million years ago (Riese et al., 2005). The Riese et al. (2005) study sampled waters from over 100 CBM wells and examined chemical and isotopic differences across the basin. The geochemical results showed the areal distributions of different water geochemical types ("fingerprints") and a lack of coherent geochemical development along previously assumed regional flow paths from basin edges to the center of the basin (anticipated in the classical "confined aquifer" model). The geochemical patterns were consistent with compartmentalization of the basin into discrete hydrogeological zones with different water qualities.

The data also support the idea that Eocene and post-Eocene (younger than about 34 million years) uplift of the basin may have caused hydraulic conductivities in the coalbeds to decrease even further due to gas desorption from the coals and to effectively isolate those aquifers. Geochemical and geological evidence suggests that later (Miocene to Holocene, or about 23 million years ago through more recent time) geological events changed the stress

BOX 2.2
Age of Groundwater

Hydrogeologists can test the validity of their conceptual models of groundwater flow systems, including predictions of where groundwater may recharge and discharge, by determining the approximate age of groundwater since it entered the subsurface as precipitation recharge. Fundamentally, an answer to the question "How old is the water?" can be determined geochemically (Bethke and Johnson, 2008). Knowing the age of groundwater, even within an order of magnitude, bears greatly on whether the water extracted from aquifers can be replenished by precipitation within human time frames, or can be considered "fossil" or ancient, nonrenewable water much like solid mineral resources such as coal and metals. Furthermore, directly determining the age of water sampled along subsurface flow paths also can be used to evaluate regional hydraulic properties used to calculate extractable water volumes. For decades, hydrogeologists have used various isotopes and other tracers to estimate groundwater age (Clark and Fritz, 1997).

In groundwater "age dating," hydrogeologists assume simple plug flow (see figure below) and then correct age dates with respect to chemical processes (e.g., methane formation affecting carbon-14 dates) and hydrodynamic processes (e.g., diffusion of isotopes into fine-grained rocks or sediments surrounding the aquifer in question). Because of these complexities and others (see Bethke and Johnson, 2008), isotopic dating of groundwater usually can reliably be done at order-of-magnitude accuracy. In other words, analysis of a full suite of isotopes in groundwater can determine if the water is a few years old, tens of years old, hundreds of years old, thousands of years old, or millions of years old.

Isotopic age dating of water is based on elements that have multiple possible masses because of variable numbers of neutrons in their nucleii. For example, the most common forms of isotopically stable carbon have atomic weights of 12 and 13 atomic mass units (written as ^{12}C, ^{13}C), in order of decreasing frequency. Isotopically stable hydrogen in water can have atomic weights of 1 or 2 atomic mass units (written as ^{1}H, ^{2}H). Oxygen can have atomic weights of 16, 17, and 18 atomic mass units (written as ^{16}O, ^{17}O, and ^{18}O).

Some heavy isotopes of individual elements (those with highest atomic weights), particularly those of hydrogen and oxygen in water and carbon in organic and inorganic materials are sorted (fractionated) from their lighter isotopes as they move through the hydrological cycle and become involved in certain biochemical processes. For example, the fractionation of lighter from heavier hydrogen and oxygen in water causes water from precipitation

field and allowed deep fracture networks to propagate up through the rock units. These fractures enhanced the connectivity of otherwise isolated portions of the reservoir and now allow the CBM wells to effectively "mine" the connate water of the sedimentary formation. These connate waters were trapped at the time the original sediments were deposited tens of millions of years ago and are not being recharged.

The various datasets show that outcrops of the Fruitland Formation are not a significant mechanism for recharge of the coal aquifers. Rather, groundwater discharges to the surface at these outcrops in seeps that may have been active for millennia. Moreover, methane in the deep coal does not hydraulically connect to methane gas seeps at outcrops,

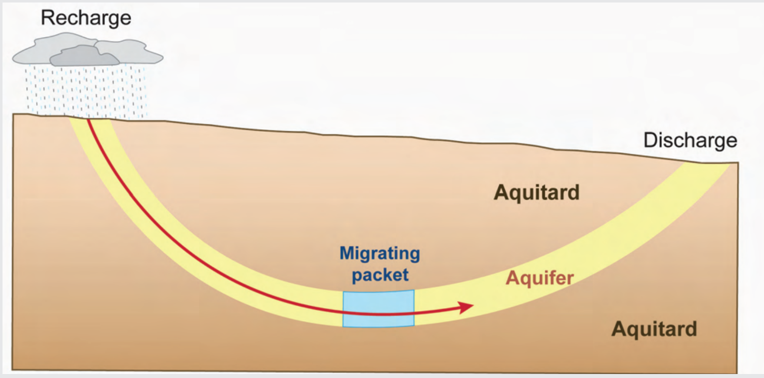


FIGURE Conceptual diagram for determining groundwater age using isotopes. Water moving in the aquifer is assumed to move as "packets" or "plugs" in pipeflow fashion from an area of recharge to an area of discharge. However, few aquifers are so simple, and a combination of hydraulic and geochemical processes can lead to incorrect estimates of ages for the water. Therefore, order-of-magnitude dating is considered realistic for most cases in which groundwater is "dated" using isotopes. SOURCE: Bethke and Johnson (2008). © 2008 by Annual Reviews, Inc. Reproduced by permission of Annual Reviews.

to become systematically "lighter" from low to high latitudes. In other words, groundwater at high latitudes will have greater proportions of ^{16}O relative to ^{18}O than does groundwater at lower latitudes.

Other isotopes, known as radiogenic isotopes, radioactively decay at known rates. Carbon-14 and tritium (^{3}H) are the most widely used radiogenic isotopes in hydrogeology. Carbon-14 forms from bombardment of atmospheric nitrogen by cosmic radiation. Large amounts of tritium were injected into the hydrological system by thermonuclear tests in the late 1950s through the 1960s. Other radioactive isotopes that may be used to "date" the age of water include krypton, argon, chlorine, and iodine. Because the rates of radioactive decay are known, these isotopes behave as natural clocks, allowing hydrogeologists to measure directly how long the water has been in aquifers, at least to the order-of-magnitude scale, when these isotopes are present in the water. Details on the methodology of the approaches can be found in Clark and Fritz (1997) and Kazemi et al. (2006).

further documenting the hydrogeological compartmentalization of the San Juan Basin (Riese et al., 2005).

Oldaker and Fehn (2005) report that surface waters and shallow groundwater are less than 60 years old in the Raton Basin but that produced water from CBM wells more than 1,800 feet deep could be at least 1.2 million years old, based on tritium (^{3}H), carbon-14, and chlorine isotope analyses. Although comprehensive isotopic studies similar to those in the San Juan Basin have not yet been conducted in the Raton Basin, these results suggest a conceptual model for CBM water in the Raton Basin similar to the San Juan Basin, particularly given the common depositional environments for the coals in the two basins.

If proven more regionally correct, Raton Basin CBM water may also consist primarily of fossil water, which occurs in compartmentalized methane-bearing coalbeds.

Today, the Raton and San Juan basins receive minimal recharge to their groundwater systems as a result of arid climate conditions. Although the groundwater systems and their sources of recharge are complex and not fully understood, the presence of high TDS waters supports the lack of recharge, as does the discontinuity or compartmentalization of all coal deposits that would further minimize recharge to coalbeds. Although removal of water from coalbeds during CBM operations may induce some degree of leakage of water over time into the coalbeds from surrounding finer-grained rocks and potentially from other aquifers through deep fracture zones, CBM water at depth does not appear to be a "renewable" resource in the San Juan and Raton basins, based on the suite of data available.

Powder River Basin

Few studies have been conducted specifically to date the age of groundwater in the Powder River Basin, but existing results indicate that some of the CBM produced water may be thousands of years old. Geochemical analysis from the eastern portion of the basin has shown that much of the deeper groundwater associated with CBM has no tritium (^3H), implying the water is at least 50 years old (Bartos and Ogle, 2002). Preliminary carbon-14 dating of dissolved inorganic carbon in CBM water appears to show water that is radiocarbon "dead," implying it is at least 14,000 years old.[7] These results are significant since the samples were taken only a few miles from presumed coalbed recharge areas at the land surface. Brinck et al. (2008) and Frost et al. (2010) concluded from evaluation of geochemical evolution of CBM produced water in proximity to recharge areas that the influence of recharge at outcrop sites likely does not extend more than 2 to 4 kilometers (1.2 to 2.4 miles) beyond the recharge sites. Correspondingly, the water in relatively close proximity to recharge sites is likely recent in geological perspective, whereas CBM water toward the center of the basin may represent "older" water. These results provide some constraints on recharge rates being slow or relatively inhibited in the studied areas of the Powder River Basin.

Sharma and Frost (2008) further determined that the isotopic composition of dissolved inorganic carbon associated with CBM produced water can be readily distinguished from the isotopic composition of dissolved inorganic carbon found in surface water and groundwater of the Powder River watershed. This type of distinction allows for easy long-term monitoring to determine the extent to which in situ and surface-discharged CBM produced water moves within the subsurface and in receiving streams. Campbell et al. (2008) determined from strontium isotopic analyses in groundwater and produced water that some

[7] C.D. Frost, presentation to the committee, June 2, 2009.

coal aquifers were hydraulically confined while others were not and that faults may provide some, although limited, connectivity for fluid migration between coal formations. Sharma and Frost (2008) suggested the same, based on carbon isotope analysis. These study results are the first of their kind to attempt to describe movement of CBM produced water with these types of isotopes. These studies are explored further in Chapter 5.

Powder River Basin coalbeds also appear to contain some younger water than do the coalbeds from the San Juan or Raton basins, particularly near the outcrop areas at basin margins, which serve as recharge avenues. Additionally, the CBM produced water of the Powder River Basin has lower concentrations of solutes due to some combination of the origins of the coals in freshwater settings and subsequent interaction of the water in the coals with percolating surface water (see also "Geochemical Foundations" below).

Case Study Summary

With respect to CBM basins, isotopic and other data in the San Juan Basin demonstrate that much of the produced water may not be a renewable resource because of its great age compared to human lifetimes. Water extracted from the San Juan Basin is fossil water that has not been renewed for tens of millions of years. For the Raton Basin and at least some portions of the Powder River Basin, away from outcrop recharge areas, the data are fewer and not comprehensive, but similar results are suggested. Although regionally pervasive, the discontinuous nature of the coalbeds has led to limited ability for water to pass through the coals under gravity flow, even in cases where permeability within a coalbed may be relatively high.

GEOCHEMICAL FOUNDATIONS

In addition to geological and hydrogeological constraints on the volume of CBM produced water, analysis and understanding of the various management approaches to CBM produced water also require an introduction to CBM produced water chemistry. The two primary constituents of CBM water are sodium bicarbonate ($NaHCO_3$, or baking soda) and sodium chloride (NaCl, or table salt; Rice and Nuccio, 2000). Constituents appearing in smaller quantities in produced water include calcium, magnesium, potassium, and barium, whereas elements such as aluminum, ammonia, selenium, arsenic, iron, manganese, boron, copper, and zinc are sometimes present in trace amounts (McBeth et al., 2003). Typically, CBM produced water contains only minimal amounts of fine, inorganic particulate matter, otherwise known as coal fines. In some instances, facultative[8] iron-oxidizing bacteria and degraded methanogenic bacteria may also be present in small amounts.

[8]Facultative organisms are capable of respiration in the presence of oxygen but are also capable of fermentation.

A series of geochemical processes remove sulfate through oxidation/volatilization and calcium and magnesium by precipitation or ion exchange/adsorption from CBM water; these processes leave the CBM water with substantially more bicarbonate and sodium (see Box 2.3). However, the TDS concentration of CBM produced water ranges from fresh to saline (i.e., 200 milligrams per liter [mg/L] to 170,000 mg/L) because of variable amounts of sodium, bicarbonate, and chloride (see Table 2.2). The recommended TDS limit for drinking water is 500 mg/L; for beneficial use, such as irrigation in Wyoming, the limit is 2,000 mg/L; and for wildlife and livestock watering in Wyoming, the limit is 5,000 mg/L (EPA, 2009; Wyoming DEQ, 2005). For comparison, seawater has a TDS of approximately 35,000 mg/L. In addition to TDS, sodium in CBM produced water is of interest as it relates to the consideration of CBM produced water for irrigation. A measure that is used to determine the influence of sodium on soils and plants is related to the sodium adsorption

BOX 2.3
Geochemical Processes and Their Control on CBM Water Composition

Three geochemical processes control the fact that CBM water contains substantially more bicarbonate and sodium than magnesium, calcium, and sulfate: (1) microbial reduction of sulfate contributed by dissolving the mineral gypsum, or reduction of sulfate at depth, which may release bicarbonate; (2) removal of calcium and magnesium by ion exchange, which releases sodium, and by precipitation of calcite ($CaCO_3$); and (3) enhanced dissolution of sulfide minerals and organic matter oxidation in water recharge areas, both of which generate acid.

Brinck et al. (2008) schematically show how these processes generically occur along groundwater flow paths in the Powder River Basin (see figure below). The geochemical processes governing the evolution of sodium bicarbonate-dominated waters have been known for an extensive period of time because of the occurrence of such waters, absent methane, along the Atlantic and Gulf coastal plains (Foster, 1950; Chapelle and Knobel, 1983). In the case of the CBM water in the Powder River Basin, where coalbeds are relatively shallow in comparison to the other western CBM basins, much of the methane formed is related to geologically recent microbial processes. However, in basins where CBM is produced during lithification (the transformation of buried sediments to rock like material) of much deeper strata, the CBM is related to the thermogenic chemical, physical, or biological change experienced by the sediment and organic debris after its initial deposition and during and after the lithification processes that formed the coal. CBM produced waters of the San Juan, Raton, Piceance, and Uinta Basins also have a chloride signature which is not shown in the conceptual diagram of Brinck et al. (2008). See also Figure 2.9.

ratio (SAR; a numeric expression of the concentration of sodium, relative to the concentration of calcium and magnesium in produced water; see also Chapter 5 for discussion of issues related to TDS and sodium in CBM produced water).

A comparison of representative principal salt constituent concentrations of water produced from major CBM basins in North America illustrates consistently elevated concentrations of sodium and bicarbonate and relatively (in most cases substantially) lower concentrations of calcium, magnesium, and sulfate (see Figure 2.9). Also evident are the substantially lower chloride and TDS concentrations in waters produced from the Powder River Basin, compared to waters from the other basins (see earlier sections of this chapter). The Powder River Basin contains primarily sodium bicarbonate-type formation water, whereas waters from the Piceance, Uinta, Raton, and San Juan basins contain sodium bicarbonate/chloride-type water.

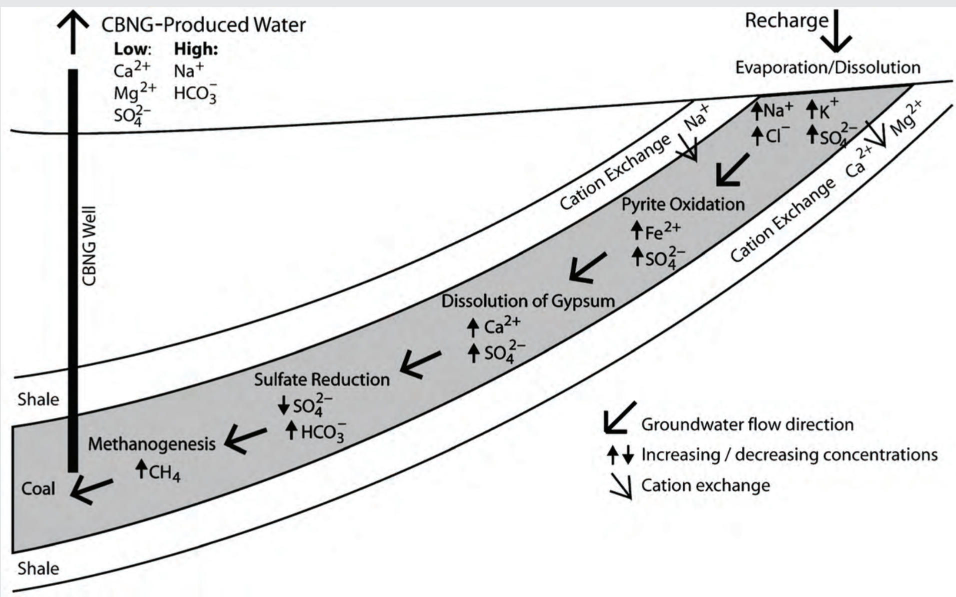


FIGURE Conceptual diagram of the geochemical evolution of CBM waters in the Powder River Basin shows biogeochemical processes that occur during the flow of groundwater from recharge areas downward through a coalbed to the point of extraction from a CBM well. Oxidation of the mineral pyrite, for example, may release iron and sulfate, while dissolution of the mineral gypsum may release calcium and sulfate. Reduction of sulfate at greater depths may result in release of bicarbonate. Methanogenesis results in the release of methane within the coal. SOURCE: Brinck et al. (2008). © 2008 by American Association of Petroleum Geologists. Reproduced by permission of AAPG whose permission is required for further use.

TABLE 2.2 Range of Total Dissolved Solids (TDS) in mg/L for CBM Produced Water from each Western Basin Compared to TDS for General Water Types and Water Quality Standards

	TDS in mg/L
Western CBM basins	
Powder River	250 to greater than 3,000
San Juan	10,000 to greater than 100,000
Raton	900 to 30,000
Uinta	6,350 to 42,700
Piceance	Greater than 10,000
General water types	
Fresh water	Less than 1,000
Saline water	Greater than 1,000
Seawater	35,000
Water quality standards	
U.S. Safe Drinking Water Act (secondary standard)	500
Wyoming agriculture standards (Class II)	2,000
Wyoming livestock standards (Class III)	5,000

NOTE: Both TDS and salinity can be used to measure water quality. TDS is a quantitative measure of all residual dissolved minerals after evaporation and is generally expressed as mg/L. Salinity measures the concentrations of dissolved salts in the water volume. Salinity may be measured by TDS, electrical conductivity, or osmotic pressure. Where sodium chloride and sodium bicarbonate are known to be the dominant minerals in a sample of water, such as in waters of the western basins, high TDS will often indicate high salinity.
SOURCES: ALL Consulting (2003); S.S. Papadopulos & Associates (2007); water.usgs.gov/watuse/wu-glossary.html (accessed July 6, 2010); www.watereuse.org/information-resources/about-desalination/glossaryd (accessed July 6, 2010); Wyoming DEQ (2005).

Generally, TDS concentration ranges from the hundreds to thousands of milligrams per liter in produced water in the basins where sodium bicarbonate dominates, such as in the Powder River Basin, whereas TDS concentrations can exceed tens of thousands to more than 100,000 mg/L where sodium chloride dominates the chemistry of the CBM water, such as in the San Juan Basin (Table 2.2). In the Powder River Basin, much of the geochemical signature of the produced water is derived from water-rock interactions (Box 2.3).

Jackson and Reddy (2007) report concentrations of trace elements and volatile organic compounds (Gas Research Institute, 1995; Rice et al., 2000) for produced water in the Powder River Basin (see also Jackson and Reddy, 2010). Some metals, such as barium, appear to have concentrations close to the solubility of controlling minerals (e.g., barite).

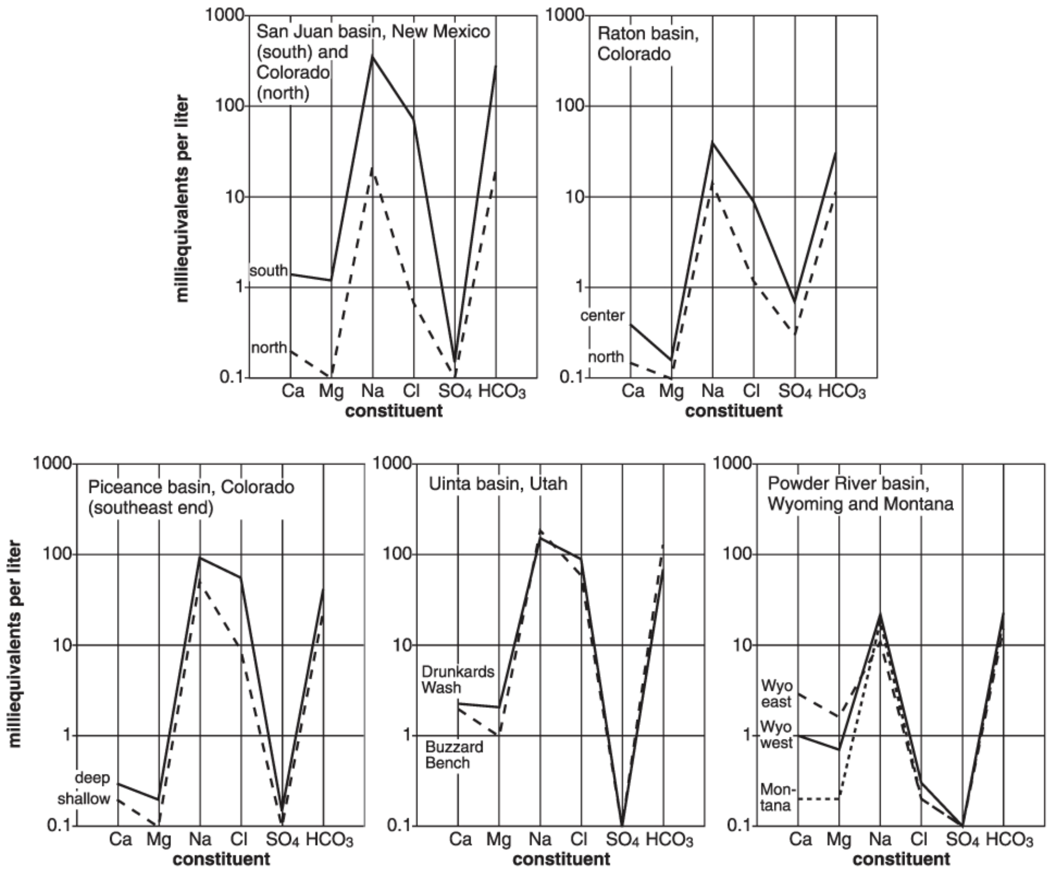


FIGURE 2.9 Predominant dissolved chemical constituents of typical CBM produced water from major methane-producing basins. Note the much higher concentrations of chloride associated with the San Juan, Raton—Colorado portion, Piceance, and Uinta Basins compared to the Powder River Basin. Note also the difference in concentrations in sodium and bicarbonate within the San Juan Basin where concentrations decrease from south (New Mexico) to north (Colorado). Data sets examined from the New Mexico portion of the Raton Basin indicated values similar to those in the Colorado portion (Haley, 2004). For ease of plotting the data, millequivalents per liter on the vertical axis normalizes milligrams per liter to both the number of atoms present per solute per liter and the valence, or charge, of the ions. SOURCE: Van Voast (2003). © 2003 by American Association of Petroleum Geologists. Reproduced by permission of AAPG whose permission is required for further use.

NOTE: Milliequivalent is a unit of measure denoting one-thousandth of a molar equivalent of a substance. An "equivalent," in the case of Figure 2.9, refers to the amount of a substance (e.g., calcium) that supplies one mole of charge (positive or negative). Because calcium has a charge of +2, one mole of calcium provides two equivalents of charge. Therefore, a 1 milliequivalent/L solution of calcium is equal to a 0.5 millimole/L solution. For ions with a single charge, such as sodium and bicarbonate, one milliequivent/L is equal to one millimole/L. To convert millimole/L to mg/L, multiply by the molecular weight of the substance.

Potentially toxic metals, such as arsenic, lead, and chromium, are generally found at concentrations less than most water quality standards in certain locations (Jackson and Reddy, 2007; see Table 2.3).

Once at the surface, CBM produced water also undergoes chemical changes associated with atmospheric equilibration and mixing with in-stream and soil-adsorbed elements. Aquifer mineral and coal composition, oxidation state, pH, sorption to aquifer mineral surfaces, and the extent to which solids precipitate along water flow paths in the aquifer all control macro- and trace element concentrations. Patz et al. (2006) documented changes in concentrations of trace metals in surface water in the Powder River Basin as such waters moved downgradient, below produced water discharge points. McBeth et al. (2003) determined that soluble salt and trace metal concentrations in surface storage ponds may increase or decrease depending on time, the underlying soil and rock material, and the

TABLE 2.3 Concentrations of trace elements (µg/L) in CBM waters in outfalls and surface impoundments in the Powder River Basin: Little Powder, Powder, and Tongue River watersheds.

	Little Powder River		Powder River		Tongue River	
	Outfalls	Disposal Ponds	Outfalls	Disposal Ponds	Outfalls	Disposal Ponds
Aluminum	304±132	573±266	181±80.7	251±95.0	1,817±1,174	361±162
Arsenic	0.75±0.75	9.74±6.74	0.75±0.75	3.75±0.75	0.75±0.75	1.50±0.75
Barium	614±49.4	334±35.7	514±98.9	284±61.8	271±26.1	130±23.3
Boron	99.3±4.76	126±19.2	141±21.5	164±12.3	109±6.81	124±6.81
Cadmium	<1.12±1.12	<1.12±1.12	<1.12±1.12	<1.12±1.12	<1.12±1.12	<1.12±1.12
Chromium	8.84±1.04	8.84±1.56	12.0±2.60	11.4±1.56	8.32±1.56	9.36±1.56
Copper	10.8±1.27	19.1±4.45	7.63±2.54	19.7±1.91	10.8±1.91	17.2±1.91
Iron	124±11.2	217±107	81.0±13.4	203±89.9	71.5±34.1	145±46.4
Lead	<2.07±2.07	<2.07±2.07	<2.07±2.07	<2.07±2.07	<2.07±2.07	<2.07±2.07
Manganese	12.6±3.85	11.5±8.24	8.24±2.20	3.30±1.10	7.69±2.75	7.14±2.20
Molybdenum	<0.96±0.96	2.88±1.92	0.96±0.29	1.92±0.96	<0.96±0.96	1.92±0.96
Selenium	1.58±0.79	1.58±0.79	1.58±0.79	2.37±0.79	0.79±0.79	0.79±0.79
Zinc	7.85±1.96	9.15±1.96	7.19±1.96	10.5±3.27	10.5±3.92	18.3±5.23

NOTE: Outfalls refer to direct discharges of from water separated from individual methane wells. Disposal ponds are containment structures that store the discharge water from multiple outflows (see Chapter 4). Mean values (µg/L) plus one standard deviation are shown for each constituent. SOURCE: Jackson and Reddy (2007). Figures converted from micromoles per liter in the original data source to micrograms per liter in this table.

degree to which mixing occurs in holding ponds (see also Chapters 4 and 5). However, in many circumstances—particularly in Colorado and Wyoming where produced water is present on the landscape—the spatial distributions, concentrations, and fate of trace elements in the water remain uncertain given the minimal sampling and analysis available (see also Chapter 5).[9]

In contrast to the studies outlined above that examined inorganic carbon, trace concentrations of dissolved organic substances may also be present in some CBM produced waters, although these substances in CBM produced waters are neither well documented nor researched. Phenols, biphenyls, heterocyclic compounds, polycyclic aromatic hydrocarbons (PAHs), and other organic constituents have been measured in some produced waters, with PAHs being the most common organic substance detected or measured. Orem et al. (2007) report microgram per liter (μg/L) concentrations of organic compounds in CBM produced waters in the Powder River Basin, with PAH values up to 23 μg/L. The committee was unable to find other data regarding organic substances dissolved in CBM produced waters of the other western basins.

GROUND- AND SURFACE WATER CONNECTIVITY AND GROUNDWATER MODELING: DATA GAPS AND UNCERTAINTIES

Concern over management of CBM-produced water stems largely from two factors: water quantity and quality on local and regional watershed scales. Litigation during the past decade has been extensive, with plaintiffs registering concerns over numerous water quality and quantity issues and their effects (see also Chapters 3 and 5). Additionally, a number of research projects have involved either monitoring and data gathering or modeling in an attempt to define the extent of local or regional water resource responses to CBM produced water withdrawals and discharges. However, for the purposes of planning CBM produced water management, questions remain with regard to the effects of large-scale, localized, regional, and/or basin-wide withdrawals; deep-well reinjection; discharge for disposal through infiltration or evaporation; and release of treated or untreated CBM water to ephemeral and perennial streams. For purposes of evaluating these various management options on water quality and quantity (discussed in detail in Chapters 4 and 5), data to determine the connectivity of groundwater and surface water and groundwater modeling are necessary. The gaps and uncertainties related to connectivity and modeling conclude the discussion in this chapter.

[9]D. Baldwin, Colorado Oil and Gas Commission, personal communication, January 6, 2008.

Data Gap to Establish Surface Water and Groundwater Connectivity

Establishing quantitatively the extent to which CBM-producing formations hydraulically connect to surface waters and major aquifers is necessary to predict the effects of CBM water withdrawal and management on surface water and groundwater quantity and quality. As discussed above, the only study that included sufficient geochemical, geological, geophysical, hydrological, and other data to establish the degree of hydraulic connectivity between methane-bearing coalbeds and surface and shallow groundwater was conducted in the San Juan Basin (Riese et al., 2005). Such data are needed to assess fundamental aspects of the groundwater flow system, the water level (potentiometric surface) and how it changes, surface water and groundwater interaction, calculations or quantitative assessments of recharge rates, and discharge areas for major streams flowing into and across CBM basins. Because comprehensive data and analyses of this nature are lacking for other western CBM basins, the committee considers this a significant information gap.

Gaps with Modeling Groundwater Flow

Although natural systems are complex, numerical models of groundwater flow in CBM basins have used fairly simple approaches in which water is modeled to move uniformly within relatively homogeneous aquifers. Thus, interactions that might occur between local, shallow streams and groundwater and deep CBM-associated waters may not be adequately represented by the model parameters. Independent and comprehensive data are needed to test and confirm the validity of the results of groundwater models for CBM basins beyond calibration to water level (the potentiometric surface). In some cases where groundwater models are used to characterize groundwater flow, the model results have not been rigorously examined through a combination of sensitivity analysis, history matching, and using multiple lines of calibration (e.g. Anderson and Woessner, 1992; ASTM, 2000). Understanding model limitations and uncertainties becomes particularly important when results of models may be used to assess the longer-term consequences to groundwater levels from CBM-related water-pumping activities.

In the Powder River Basin, for example, one modeling study indicated effects from CBM pumping that included depression of the potentiometric surface of coal aquifers, which serve as local water sources, and potential loss of stream flow for as long as 50 years (Meyers, 2009). Simple mathematical models (e.g., the Glover-Balmer method) related to the effects of regional CBM withdrawals in the San Juan Basin have also been employed and model results interpreted to suggest stream depletion and drawdown of the potentiometric surface of coal-bearing formations within 20 miles of their outcrop area (e.g., S.S. Papadopulos & Associates, Inc., 2006; Hathaway et al., 2006). In the case of the San Juan Basin where other studies yielded results with sufficient isotopic age dating (Box 2.2), the data show CBM produced water is primarily fossil groundwater that has not been recharged for thousands to tens of millions of years, which contradicts the model results for stream depletion and drawdown. Similarly comprehensive data to test the results from the Powder River Basin modeling study are not currently available.

The Glover-Balmer method incorporates assumptions based on pumping water from a well constructed in an artesian aquifer. Many of these assumptions are violated when applied to pumping from multiple wells in a complicated watershed (e.g. Spalding and Khaleel, 1991; Sophocleous et al, 1995). For example, the method assumes that the aquifer is "isotropic" (permeability the same horizontally and vertically) and "homogeneous" (the same material everywhere). In CBM basins, interlayered coarse- and fine-grained rocks occur and generate notable heterogeneous and non-isotropic conditions. The method also assumes that the aquifer extends to infinity. This assumption can be valid locally when a well is pumped, but does not apply to a basin where geologic units pinch out or disappear over short distances as they do in the western CBM basins. The Glover-Balmer method is only useful as a first approximation, at best, if at a watershed scale.

Although modeling may be useful for broad assessment of possible hydraulic relationships in CBM basins, numerical models of hydrogeological systems currently do not yield unique results. Different, multiple combinations of input parameters can produce the same overall results for measurements of water levels and other hydrological data typically used to calibrate the model (e.g., Oreskes et al., 1994; McDonnell et al., 2007). Furthermore, current models cannot yet characterize complex water-rock interactions, differences in hydraulic properties, or boundary conditions in CBM basins. Thus, testing the results and assumptions of numerical and other groundwater models against data from the field or area being modeled is important in order to establish a level of reliability that is suitable for making management decisions. For example, if a model predicts decreasing flow in streams because of CBM production, then low-flow measurements in the rivers presumed to be affected are necessary to test the model results. Similarly, if modeling suggests that streams receive water from coalbeds to maintain baseflow, then chemical measurements in the streams are necessary to determine if CBM "fingerprints" (chemical constituents typical of CBM formations) are present in the water.

Despite these limitations, groundwater models of basins can predict general travel time of groundwater along flow paths, and these predictions can be tested by age dating the water. Until the gap is filled between the results of groundwater models and the necessary data to test them, care is urged with regard to using model results alone to make regulatory or other determinations regarding produced water management. The ability to place more reliance in the future on outputs of models that more closely resemble natural complexities of the hydraulic conditions of CBM basins necessitates demonstrating better convergence between existing model results and data collected and analyzed from the basins.

CHAPTER SUMMARY

Quantitative understanding of the degree and extent of connectivity between surface water and shallow groundwater systems and methane-producing coalbeds is important when evaluating the potential effects of CBM extraction, coproduction of water, and subsequent management of the produced water. The degree of connectivity bears on the groundwater flow system, surface water and groundwater interaction, calculations or quantitative assessments of recharge rates, and discharge areas for major streams flowing into and across CBM basins. Effective management of water produced during CBM extraction is contingent on establishing to what degree surface water and groundwater resources may be depleted, degraded, supplemented, or enhanced and over what time periods.

For the western CBM basins, methane developed together with coal over millions of years from different fluvial, lagoonal, and nearshore freshwater and marine settings that contained organic material, which was progressively buried. Although these coals are regionally pervasive, individual coalbeds are discontinuous, reflecting the original meandering and discontinuous environmental setting in which plant matter was deposited and subsequent tectonic activity. Methane in the coal is held adsorbed to the coal surfaces by surrounding water pressure; water in the coal may represent original (connate) water from the environment in which the organic material was initially deposited and/or some "younger" water that has percolated from the surface or shallow groundwater into the coalbeds. Technology used to extract methane from coalbeds relies on pumping the water from the coalbed to the surface to reduce the water pressure and allow the methane to be released from the coal and up the well bore.

Variations in regional geological and hydrogeological histories for the western CBM basins have had direct bearing on the subsurface depth of the coalbeds and the differences in the volumes of methane and the volume and chemistry of the associated produced water. In the Powder River Basin of Montana and Wyoming, relatively high CBM produced water volumes with generally low dissolved salt concentration in comparison to other western CBM basins are due to the occurrence of methane-bearing coalbeds with relatively high permeability and water-filled porosity. CBM-produced water volumes are lower in the San Juan and other western CBM basins, where the methane-producing coalbeds typically occur at greater depths than in the Powder River Basin and have correspondingly lower permeabilities. The deeper coalbeds yield lower water-to-gas ratios and produced water with higher dissolved salt concentrations.

Because many of the coal seams and beds in these western basins are discontinuous, the way in which water in the coal and surrounding sedimentary rocks migrates and is replenished is more complicated than what simple hydrological systems predict. Where discontinuities and/or low permeability exist in the coalbeds, groundwater may move very slowly and natural replenishment of coalbeds after water is withdrawn may not occur in human lifetimes or even in thousands to millions of years. Such "old" or "fossil" water is considered a nonrenewable resource once it is withdrawn.

Several studies using geological, geochemical, geophysical and hydrological data indicate that the water in the San Juan Basin is probably thousands to tens of millions of years old, except at recharge areas—in other words, produced water from CBM extraction in the San Juan Basin is fossil water that will not be renewable over human lifetimes. Preliminary data from the Raton Basin indicate that some of the produced water from CBM extraction may also be fossil water. Although a few isotopic studies have suggested some of the CBM produced water in the Powder River Basin is fossil water, more detailed analyses incorporating water chemistry, isotope study, and geophysical data collection—such as those done in the San Juan Basin—would clarify the extent to which fossil water and/or recharge with younger water occurs in the Powder River Basin. Using a full suite of geological, geochemical, hydrological, and geophysical data, and particularly using isotopic analyses to approximate the age of the water, will help determine whether the produced water is a resource that will be depleted by CBM production or replenished over shorter timescales.

Lack of renewability of the water resource that is extracted during CBM production is an important variable to consider in determining produced water management strategies. The renewability of water has implications for the degree of hydraulic connectivity between methane-bearing coalbeds and surrounding groundwater systems and surface waters and also the intended management of the water subsequent to extraction.

Chemical constituents in the produced CBM waters from the basins vary between and within basins and reflect variability in hydrological systems. The two primary constituents of produced water are sodium bicarbonate and, to a lesser extent, sodium chloride. TDS concentrations in the western basins range from fresh to saline (200 to 170,000 mg/L). The Powder River Basin contains primarily sodium bicarbonate-type formation water and low TDS, whereas the Piceance, Uinta, Raton, and San Juan basins contain sodium bicarbonate chloride-type water at higher concentrations than in the Powder River Basin and generally high TDS. Once at the surface, water produced with methane extraction may undergo further chemical changes associated with atmospheric equilibration and mixing with in-stream and soil-adsorbed elements. Aquifer mineral and coal composition, oxidation state, pH, sorption to aquifer mineral surfaces, and the extent to which solids precipitate along water flow paths in the aquifer all control trace element concentrations.

Although groundwater modeling may be useful for broad assessment of possible hydraulic relationships in CBM basins, current models cannot yet characterize complex water-rock interactions, differences in hydraulic properties or boundary conditions present in CBM basins. As with connectivity issues, testing the results and assumptions of groundwater models for CBM basins against complete suites of data from the basins is important to provide an appropriate level of reliability of the model results.

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CHAPTER THREE

Regulatory Context for Coalbed Methane Produced Water Management

The legal and regulatory framework governing coalbed methane (CBM) produced water management in the western United States is complex, consisting of a set of interleaved federal, tribal, and state laws and principles of water rights within which CBM projects operate. In the six states identified for this study (Colorado, Montana, New Mexico, North Dakota, Utah, and Wyoming), CBM may be developed on federal, state, tribal, or private lands. Each of the six states has different regulatory approaches toward CBM permitting and produced water management. Similarly, several tribes with lands within or adjacent to basins with active CBM development have taken different approaches toward CBM production, management of CBM produced water, and/or regulations to mitigate potential impacts of CBM produced water.

This chapter reviews the significant statutory and regulatory provisions that address the management of CBM produced water in the six western states, with an aim to provide a foundation to understand the regulatory challenges of managing CBM produced water. Several recent changes to the regulatory framework affecting CBM operations in several states took place during the course of this study and the permitting processes for CBM production and CBM produced water management are continuing to evolve. The recent changes that have been made are discussed because they exemplify the complexities and challenges of managing CBM produced water and offer insight toward the way in which federal, tribal, and state governments may be considering how to manage CBM produced water in the future.

Much of the material compiled for this chapter derived from the compendium on water rights laws in 19 western states by Hutchins (2004). Two other broadly encompassing references regarding water law, western CBM production, and CBM produced water management are Bryner (2002) and the Produced Water Management Information System (PWMIS).[1] Other references are cited where applicable.

WATER RIGHTS IN THE UNITED STATES

The legal framework for water rights substantially influences the management of all produced water in the western United States, including produced water from CBM activity and from conventional oil and gas production. This section briefly describes the basic water rights laws that are applicable to a broad range of produced water issues, including those specific to CBM activities.

Water rights and water allocation programs in the United States are primarily governed by individual states and tribes. No national water rights system exists. Generally, two divergent systems are used to administer water rights at a state level. Riparian water rights[2] are more common in the eastern states. In the western states a system of prior appropriation water rights is generally applied and water rights are treated in a similar way to rights to real property: rights to water are established by actual use of the water and are maintained by continued use and need. Water rights in the western states thus can be conveyed, mortgaged, transferred, and encumbered independent from the land on which the water originates or on which it is used, as dictated by state-specific water management regulations.

Indian water rights are defined and governed by federal law that recognizes Indian tribes' property and sovereignty rights to the water on their lands and water designated as reserved for tribal use into perpetuity. Most Indian water rights are based on *Winters v. United States* of 1908 (207 U.S. 564, 28 S. Ct. 207, 52 L. Ed. 340).[3] Application of this ruling, as with the principle of prior appropriation for the states (see below), has been affected by developments in tribal regulation, federal legislation, and case law during the past century.

Each state has its own variations on the basic principles of prior appropriation, depending on custom, culture geography, legislation, and case law (see Table 3.1). In general, a water right is established by obtaining an authorization for use of a specified amount or term of use of water, through a state-issued water rights permit. The essential elements of a water rights appropriation are the diversion of water from its principal source and its application to a beneficial use. A diversion may be made by merely removing water from its natural course or location or by controlling water that remains in its natural course. Irriga-

[1]See www.netl.doe.gov/technologies/pwmis/index.html (accessed March 4, 2010).

[2]A system of allocating water among those who own land that physically touches the water body is based on the principle that land owners have the right to make reasonable use of the water. The water may be used as it passes through the property of the land owner, but it cannot be unreasonably detained or diverted, and it must be returned to the stream from which it was obtained. See www.blm.gov/nstc/WaterLaws/appsystems.html (accessed March 4, 2010).

[3]Available at supreme.justia.com/us/207/564/ (accessed July 8, 2010).

tion, mining and industrial applications, stock watering, and domestic and municipal use, for example, are commonly recognized beneficial uses. Exercising the water rights permit and using the water for a beneficial purpose formally creates a legal right to the water.

The underlying principle under prior appropriation doctrine is that water and its rights are allocated on a "first in time, first in right" basis. The earliest water users have priority over later water users ("appropriators") during times of water shortage, and water diversions and beneficial uses are fully allowed, in order of seniority of the water right, until the available water supply is exhausted. The concept of establishing a "priority date"—the date when the first water user obtains priority over other users—is thus very significant. Interstate water rights agreements, such as the Colorado River Compact, the Upper Colorado River Basin Compact (see Appendix E), and the Yellowstone River Compact of 1951 are illustrative in this connection. The Yellowstone River Compact (Pub. L. No. 82-231, 65 Stat. 663) forms the basis of ongoing claims related to the impacts CBM development on the water rights of Montana and the Northern Cheyenne Tribe under the Compact (see also Appendix F) (SCOTUS, 2010).

Beneficial use of water is a fundamentally important consideration in western water law under which public waters are obligated to be used for a useful or beneficial purpose. The appropriator can use only the amount of water presently needed, allowing excess water to remain in the stream. Generally, once the water has served its beneficial use, any waste or return flow is required to be returned to the stream. To change either the point of diversion or the point of use of the water, a modification to an existing permit is often required. In this context the concept of "instream flow" also becomes important. Instream flow is defined as the amount of water flowing through a natural stream course required to sustain the instream values at an acceptable level. Instream "values" and/or beneficial uses may include protection of fish and wildlife habitat, migration, and propagation; recreation activities; navigation; hydropower; waste assimilation (water quality); and ecosystem maintenance. Water requirements adequate to maintain all of these uses at an acceptable level are the "instream flow requirements."[4] Each state considered in this study addresses the issue of instream flow in a slightly different manner: Wyoming, Colorado, and Utah recognize beneficial uses for some instream flows and have specific provisions and state agencies responsible for addressing instream flow issues; in Montana and North Dakota, beneficial uses for instream flows are not explicitly defined, although cases may be decided at the discretion of state agencies overseeing this water resource; and New Mexico does not recognize instream flow as a beneficial use at this time (Table 3.1).[5] The relevance of instream flow for CBM produced water relates to managed discharge of some CBM produced water into perennial and ephemeral streams.

[4]See www.fws.gov/mountain-prairie/wtr/water_rights_def.htm (accessed March 9, 2010).
[5]See www.blm.gov/nstc/WaterLaws/stateflowsummary.html (accessed March 9, 2010).

TABLE 3.1 Approaches to Administering Water Rights and Managing CBM Produced Water in Six Western States

	North Dakota	Montana	Wyoming
Water rights doctrine	Prior appropriation doctrine; all water is property of public, with water rights allocated for beneficial uses	Prior appropriation doctrine; all water is property of the state of Montana, to be used for the benefit of the people	Prior appropriation doctrine; all natural waters within the state are property of the state, with water rights allocated for beneficial uses
Designated beneficial uses	Includes domestic, municipal or public, livestock, irrigation, industrial (including mining and manufacturing), fish, wildlife, and recreational activity uses	Defined as a use of water for the benefit of the appropriator, other persons, or the public; including, but not limited to, agriculture, commercial, domestic, dewatering, erosion control, fire protection, fish and fish raceways, geothermal, industrial, irrigation, mining, municipal, navigation, power, pollution abatement, recreational uses, sediment control, storage, stock water, waterfowl, water lease, and wildlife	Recognized beneficial uses include irrigation, municipal, industrial, power generation, recreational stock, domestic, pollution control, instream flows, and miscellaneous[a]
Groundwater policy	Prevent the contamination of public water supplies, including surface and groundwater sources	Groundwater use in declared "controlled groundwater basins" (e.g., Powder River Basin) is governed by specific regulations to protect limited or declining supplies	Surface water and groundwater are treated as hydrologically separate; however, if upon investigation, a hydrological connection is found between the two sources, the water use is treated as one source

Utah	Colorado	New Mexico
Prior appropriation doctrine; all water is property of public, with water rights allocated for beneficial uses	Prior appropriation doctrine; although water is considered to be the property of the state, a property right exists in the priority to use water	Prior appropriation doctrine; all natural waters within the state are declared to be public and subject to appropriation for beneficial use
Agriculture, culinary, domestic, industrial, irrigation, manufacturing, milling, mining, municipal, power, stock watering, instream flow (recreation and preservation of the natural stream environment), storage (including water supply, aquatic culture, and recreation)	Statutorily defined as "the use of that amount of water that is reasonable and appropriate under reasonably efficient practices to accomplish without waste the purpose for which the appropriation is lawfully made." Specific uses are not designated but have included aesthetics and preservation of natural environments, augmentation, commercial, domestic, fire protection, fishery, geothermal, groundwater recharge, industrial irrigation, livestock, minimum flow, municipal, power, recreation, silvicultural, snowmaking, wildlife watering, wildlife habitat, instream flow	No official state designations; however, beneficial uses in the past have included agriculture, commercial, domestic, industrial, recreational uses, state conservation goals, and stock watering
State divided into "groundwater areas;" policies are similar to surface water, but permit approval criteria may differ by area	Must obtain permit from State Engineer to drill a well; if "tributary" to a surface stream, use of the groundwater falls under the prior appropriation system, and water rights must obtained; in nontributary aquifers the water is allocated based on the percentage of land owned on the surface above the aquifer	The State Engineer establishes and regulates water use in declared "underground water basins" to protect prior appropriation, ensure water is put to beneficial use, and maintain orderly development of the state's water resources

continued

TABLE 3.1 Continued

	North Dakota	Montana	Wyoming
Agency responsible for water rights	North Dakota State Water Commission, through the Office of the State Engineer	District court (for all pre-July 1, 1973, water rights) and the Water Resources Division of the Montana Department of Natural Resources and Conservation (for all post-June 30, 1973, water appropriations)	State Engineer's Office. Four regional water division superintendents and the State Engineer comprise the Wyoming Board of Control, which meets quarterly to adjudicate water rights and to consider water rights matters
Agency responsible for produced water management and permitting	North Dakota Department of Health, Environmental Health Section: oversees water quality rules and regulations, reviews and issues NPDES permits for surface discharges, and administers the UIC program	Montana Department of Environmental Quality oversees surface discharges through NPDES	Wyoming Department of Environmental Quality Water Quality Division oversees produced water discharges; has primacy for regulating UIC permits for Class I, III, and V wells and groundwater monitoring beneath impoundments; State Engineer's Office oversees construction permits for on-channel impoundments; Wyoming Oil and Gas Conservation Commission oversees construction permits for off-channel impoundments
Agency responsible for CBM operation and permitting on state and private land	North Dakota Industrial Commission, through its Oil and Gas Division	Montana Board of Oil and Gas Conservation oversees oil and gas operations, including those for CBM, and has been delegated jurisdiction by EPA over the UIC program for Class II wells	Wyoming Oil and Gas Conservation Commission responsible for permitting oil and gas wells and UIC permits for Class II reinjection wells

[a]See seo.state.wy.us/about.aspx (accessed July 8, 2010).

NOTE: NPDES, National Pollutant Discharge Elimination System; UIC, Underground Injection Control; EPA, U.S. Environmental Protection Agency.

Utah	Colorado	New Mexico
Division of Water Rights (State Engineer)	The Office of the State Engineer (Division of Water Resources with the Department of Natural Resources) administers and distributes the state's waters (water.state.co.us/); seven water courts oversee each major river basin	Office of the State Engineer
Utah Department of Environmental Quality Division of Water Quality (groundwater monitoring and compliance, groundwater discharge permitting, surface water quality and monitoring); Utah Division of Oil, Gas, and Mining regulates disposal operations for CBM produced water including Class II injection wells and impoundments	One of three agencies: Colorado Oil and Gas Conservation Commission (under Department of Natural Resources; State Engineer; Department of Public Health and Environment (CDPHE) Water Quality Control Division, depending on classification of produced water as waste or beneficial use and as tributary or nontributary. CDPHE grants permits for discharge to surface water	Oil Conservation Division of the New Mexico Department of Energy, Minerals, and Natural Resources as delegated by the New Mexico Environment Department and its associated Water Quality Control Commission
Utah Division of Oil, Gas, and Mining	Colorado Oil and Gas Conservation Commission	Oil Conservation Division of the New Mexico Department of Energy, Minerals, and Natural Resources

Because the prior appropriation system has beneficial use of the resource as its underpinning, a lack of use may result in "abandonment" or "forfeiture" of the right. Most western state laws provide for the loss of a water right if the water is not diverted and used over a specified period of time that may be as little as five years.

Adjudication of water rights is the responsibility of the State Engineer, or a designated executive branch department or District Court, depending on the state (Table 3.1). Competition for water, as well as proper enforcement of the priority system, necessitates a comprehensive scheme of administrative controls. The State Engineer's office in North Dakota, Wyoming, Utah, Colorado, and New Mexico and the Montana Department of Natural Resources and Conservation's Water Rights Bureau are charged with the development and appropriation of surface water and groundwater resources for the state. At the federal level the Bureau of Land Management (BLM) policy generally is to defer to the states in the areas of regulating the quality, beneficial uses, and appropriation of "waters of the state," which are extracted in the development of CBM. Tribes are recognized as sovereign nations by the federal government with title to tribal lands held by the federal government in the status of a trust. Tribal governments thus have authority over their lands and associated water rights (see Winters Doctrine, above) without being subject to state laws.

FEDERAL AUTHORITIES

Three federal agencies—BLM, U.S. Department of Agriculture Forest Service (USFS), and U.S. Environmental Protection Agency (EPA)—have jurisdiction over CBM development and production activities and related CBM produced water management on federal lands or on lands beneath which the federal government retains mineral ownership, such as split estate mineral development.[6] However, if a state has primacy for implementing the Clean Water Act (CWA) or for Class II injection wells under the Safe Drinking Water Act (SDWA; see below), the state shares regulatory authority on federal land. The specific responsibilities and CBM-related regulations of these agencies are described in the next section. Because some tribal lands of the western CBM basins contain commercially viable CBM reserves, tribal jurisdiction over CBM development and produced water management is also briefly described (see reference to Winters Doctrine above; also Appendix F). The various state authorities that oversee state and private lands are reviewed later in the chapter.

[6]"Split estate" refers to a situation in which the surface and subsurface rights (e.g., the right to develop minerals) for a particular land parcel are owned by different parties. When mineral rights are part of the split-estate issue, mineral rights take precedence over other rights associated with the land. Regardless, the mineral owner is required to show "due regard" for the interests of the surface owner. BLM's split-estate policy applies to circumstances in which the surface rights are in private ownership and the rights to develop the mineral resources are publicly held and managed by the federal government. See also www.blm.gov/wo/st/en/prog/energy/oil_and_gas/best_management_practices/split_estate.html (accessed May 24, 2010).

BLM

The BLM has jurisdiction over onshore leasing, exploration, development, and production of oil and gas on federal lands in the United States.[7] The magnitude and complexity of this jurisdiction with regard to CBM development are evident when the subsurface (mineral rights) and surface ownership for the Powder River Basin are examined (see Figure 3.1). A patchwork of various surface rights under federal (BLM or USFS), tribal, state, or private ownership contrasts with the extensive subsurface ownership of minerals (including oil, gas, and coal) primarily under federal (BLM) jurisdiction. When BLM issues a valid lease to extract oil and gas resources from federal lands under BLM jurisdiction, certain contractual property rights and responsibilities governing resource development are created. The BLM regulatory framework governing oil and gas operations for federal and tribal lands is contained in 43 CFR Part 3160 (Onshore Oil and Gas Operations).[8]

BLM is required to take into account the provisions of the National Environmental Policy Act of 1969 (NEPA) in its decision-making processes. Under NEPA all federal agencies must consider the potential environmental impacts of their proposed federal projects and activities and are required to conduct an environmental assessment (EA) and/or prepare a formal environmental impact statement (EIS). Actions requiring an EIS include those "major federal actions significantly affecting the quality of the human environment" (EPA, 1970). Thus, under NEPA, before implementing any major action or project in which the federal government is involved, the federal agency must consider the environmental impacts of that action.[9] An EIS requires addressing each of the following:

- the environmental impacts of the proposed action;
- any unavoidable adverse environmental impacts;
- alternatives, including no action;
- the relationship between short-term uses of the environment and maintenance and enhancement of long-term ecological productivity; and
- irreversible and irretrievable commitments of resources.

An EA is prepared when it is unclear whether an action will have a significant effect on the human environment. If it is determined that a federal action will have a significant

[7]BLM is primarily responsible for the regulation and development of federal oil and gas mineral resources under the following acts: the Mining Leasing Act of 1920 (41 Stat. 437; see BLM, 2007); the Federal Land Policy and Management Act of 1976 (43 USC 1701-1782; see BLM, 2001a); the Federal Onshore Oil and Gas Leasing Reform Act of 1987 (101 Stat. 1330-256, an amendment to the Mineral Leasing Act of 1920); the National Forest Management Act (16 USC 1600-1604); and the National Materials and Minerals Policy, Research, and Development Act of 1980 (P.L. 96-479; 30 USC 1601-1605). Many of these acts are summarized in NRC (1989).

[8]The BLM and USFS jointly prepared a manual, *The Gold Book*, which summarized surface operating standards and guidelines for oil and gas exploration and development (BLM and USFS, 2007).

[9]See ceq.hss.doe.gov/nepa/regs/nepa/nepaeqia.htm (accessed July 8, 2010).

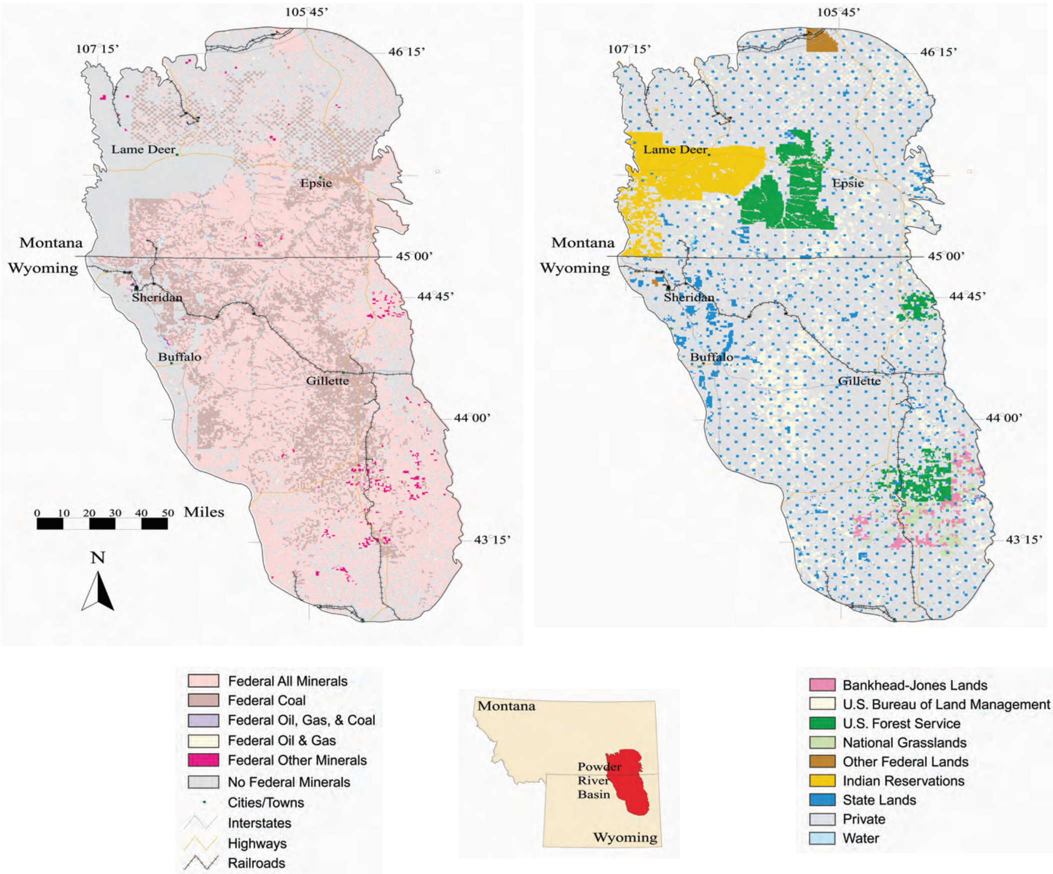

FIGURE 3.1 Comparison of subsurface (mineral rights) ownership (left) with surface ownership (right) in the Powder River Basin in 1999. Although the majority of the subsurface rights are federal (all colors except for the gray areas in the map on the left), the surface ownership is distributed among a blend of private (gray), state (blue), tribal (yellow), and federal owners. The attendant issues of split-estate ownership and responsibilities (different surface and subsurface mineral ownership) affect land and resource management. Although the committee could not find a published map of the entire Powder River Basin that displayed all current CBM well operations relative to their distribution on private, state, or federal land, the maps in this figure demonstrate the shared responsibility for CBM leasing and produced water management among the various authorities. SOURCE: Adapted from Taber and Kinney (1999).
NOTE: "Federal All Minerals" indicates federal ownership of the rights to all minerals, including oil, gas, coal, and others; "Federal Coal" indicates rights to coal minerals only; "Federal Oil and Gas" indicates rights to oil and gas and may include other mineral rights; "Federal Oil, Gas, and Coal" indicates rights to oil, gas, and coal resources; "Federal Other Minerals" indicates mineral rights not listed and may include oil and gas rights; and "No Federal Minerals" indicates subsurface mineral rights are not owned by the federal government, for example, those beneath the Northern Cheyenne and Crow tribal lands in Montana.

effect on the human environment (either through an EA or based on existing knowledge) then an EIS is prepared. EISs and EAs explore feasible alternatives to a proposed action and the likely environmental consequences of those actions. Hydrological, geological, biological, and ecological issues are among the consequences considered. EISs also consider socioeconomic (including health) impacts. Depending on the nature of a given project, archeological, historical, cultural impact analyses, and financial management plans for an action may also be addressed. Before implementing the proposed action, all of these issues must be addressed and the information in the EIS made available to the public for review and comment.

To address the management of produced water, BLM promulgated Onshore Oil and Gas Order (OOGO) No. 7 (58 FR 44354, published on September 8, 1993 with a correction to the original order [58 FR 58506] published on November 2, 1993), which applies to disposal of produced water from completed wells on federal and tribal oil and gas leases, whether from conventional oil and gas production or from CBM production. This order does not apply to approval of disposal facilities on lands other than federal or tribal lands or if the disposal method has been covered under an approved enhanced recovery project.[10]

OOGO No. 7 includes the following requirements:

- Operators of onshore federal and tribal oil and gas leases may not dispose of produced water unless and until approval is obtained from the authorized officer.
- All produced water from federal and tribal leases must be disposed of (1) by injection into the subsurface; (2) into lined or unlined pits; or (3) by other acceptable methods approved by the authorized officer, including surface discharge under National Pollutant Discharge Elimination System (NPDES) permits (see "EPA" below for discussion of NPDES). Injection is generally the preferred method of disposal.
- Operators shall submit a formal application to request approval for disposal of produced water in injection wells and in lined or unlined pits on land on the same lease as that containing the wells from which the water was produced ("on-lease disposal"); new pits on national forest lands may also require approval of the USFS.
- When requesting approval for disposal of produced water "off-lease" (disposal in a well or pit on leased or unleased federal and tribal lands that are different from the lease for the wells from which the water was produced), operators shall submit a formal notice and application, potentially also including a request for a right-of-way authorization.

[10]Enhanced recovery in the petroleum industry refers to techniques applied to an operating oil or gas field that attempt to increase (or "enhance") the amount of oil or gas that can be recovered from the field once primary extraction methods have been employed.

- For water to be disposed of in injection wells, operators must also submit a copy of the Underground Injection Control (UIC) permit (unless the well is authorized by rule).
- An application must be submitted for CBM water produced on federal lands that is to be disposed of "off-lease" on state and privately owned lands; a copy of the UIC permit for injection wells or pit permit may also be required (BLM, 1993).

Additionally, this order identifies informational requirements for injection wells and pits; requirements governing pit design, construction, maintenance, abandonment, and reclamation; requirements for other disposal methods; and reporting requirements for disposal facilities. Operators may request different considerations from the standards of the OOGO.

Collectively, the Federal Land Policy and Management Act, the CWA (see below), and related executive orders guiding BLM's management of public land and resources require the agency to comply with all federal and state laws and regulations governing water pollution that may result from BLM permitted projects and activities. Operations from the point of origin (primarily the well head) to the point of discharge are under the jurisdiction of the BLM. Operations from the point of discharge downstream are under the jurisdiction of EPA or the primacy state.

USFS

The USFS is primarily responsible for managing surface resources on national forest lands, while the U.S. Department of the Interior, through the BLM, has statutory responsibility for issuing and supervising mineral leases on all federal lands including national forests. The USFS cooperates with the Department of the Interior in administering exploration and development of leasable minerals, including the review of permit and lease applications and making recommendations to protect surface resources (USFS, 1994). For example, the USFS and BLM worked jointly to develop the EIS for the Northern San Juan Basin CBM Project. The EIS examined potential impacts of new CBM wells on USFS, BLM, state, and private land in southwestern Colorado (USFS, 2006). As is the case with BLM, the USFS is required to take into account NEPA provisions in its management of surface resources.

Bureau of Indian Affairs

The Bureau of Indian Affairs (BIA) manages 55 million acres of surface and 57 million acres of subsurface minerals estates held in trust by the United States for American Indians, Indian tribes, and Alaska Natives. The Office of Indian Energy and Economic Development within the BIA is responsible for assisting tribes in developing their energy and economic resources. The BIA Office of Trust Services' Division of Natural Resources oversees issues and provides guidance related to development and protection of natural resources, including protection of Indian water rights and fish and wildlife on Indian lands.[11]

The Omnibus Indian Mineral Leasing Act of 1938 and the Indian Mineral Development Act of 1982 require the Bureau of Indian Affairs (BIA) to authorize energy leases. The BLM processes Applications for Permit to Drill (APD), Master Development Plans, and Sundry Notices on tribal and allotted oil and gas leases in a way that is similar to federal leases. However, approval procedures, such as cultural resource and other environmental requirements, may vary depending on tribal ordinances and whether tribes have assumed the functions of a State Historic Preservation Office. Both the tribe and BIA may recommend further conditions of approval to the APD. NEPA applies to these decisions, although qualifying tribes are permitted to enforce environmental laws, set regulations that are more stringent than federal minimum standards, and regulate aspects not covered by federal laws or programs (Bryner, 2002). For processing APDs, BLM considers the BIA to be the surface management agency for all Indian lands unless a tribe has contracted the BIA realty function for its lands. Oil and gas operators are responsible for obtaining any special use or access permits from appropriate BIA and/or tribal offices (BLM and USFS, 2007).

Tribal governments each have their own departments in areas of environmental protection and natural resources. These departments are directly engaged in research, analysis, monitoring, and regulation of oil and gas development (including CBM) and environmental management in concert with relevant federal agencies (see Appendix F and next section on EPA).

EPA

The EPA's involvement in water management and environmental regulation in the area of CBM produced water involves the CWA, which deals primarily with permitting of discharges to surface waters, and the SDWA, which deals with underground injection permitting and controls. Through these Acts Congress established a process whereby primary authority could be delegated to the states and recognized tribes once they have put the appropriate authorities, statutes, and regulatory frameworks in place.

Clean Water Act

The CWA is the primary federal law in the United States governing surface water pollution.[12] The main goals of the act are to restore and maintain the chemical, physical,

[11] See www.bia.gov/ (accessed July 8, 2010).
[12] See www.epa.gov/watertrain/cwa/ (accessed March 4, 2010).

and biological integrity of the nation's waters for the protection and propagation of fish, shellfish, and wildlife and to provide for protection of human health and recreation in and on the water (e.g., fishing, swimming, boating) and to eliminate discharge of pollutants to navigable (surface) waters.[13] The act governs discharges of pollutants, defined as the addition of any pollutant to waters of the United States from any point source. The term "waters of the United States" has been further defined to include traditional navigable waters, wetlands adjacent to traditional navigable waters, non-navigable tributaries of traditional navigable waters that are relatively permanent and where the tributaries typically flow year-round or have continuous flow at least seasonally (e.g., typically three months), and wetlands that directly abut such tributaries. Responsible agencies will decide jurisdiction over other waters based on a fact-specific analysis to determine whether they have a significant nexus with traditional navigable water.

The CWA introduced a permit system for regulating point sources of pollution. Point sources[14] presently recognized and managed under the provisions of the CWA include:

- industrial facilities (including manufacturing, mining, oil and gas extraction, and service industries);
- municipal governments and other government facilities (such as military bases, municipal wastewater treatment facilities); and
- some agricultural facilities, such as animal feedlots and food-processing facilities.

Point sources may not discharge pollutants to surface waters without a permit from the NPDES. This system is managed by EPA in partnership with state environmental agencies. EPA has authorized 46 states to issue NPDES permits directly to the discharging facilities. The CWA also permits EPA to authorize tribes to issue NPDES permits if a tribe's application for eligibility to administer water quality standards and certification programs is approved by EPA. Amongst the tribes with lands located within or near to one of the CBM basins examined in this study, the Northern Cheyenne Tribe (Powder River Basin area) and Ute Mountain Ute Tribe (near the western edge of the San Juan Basin) have received approval from EPA to administer water quality standards and certification programs, although these are not specific to CBM produced water issues (see also Appendix F). In the remaining states and territories, the permits are issued by an EPA regional office. Of the six states in this study, only New Mexico is not yet authorized by EPA to issue NPDES

[13] C. Johnston, EPA, presentation to the committee, January 6, 2009.

[14] "Point source" in section 502(14) of the Clean Water Act is generally defined as "any discernible, confined and discrete conveyance, including but not limited to any pipe, ditch, channel, tunnel, conduit, well, discrete fissure, container, rolling stock, concentrated animal feeding operation, or vessel or other floating craft, from which pollutants are or may be discharged."

permits, and this responsibility continues to lie with the EPA; however, the state has entered into the process to seek this authority from EPA.[15]

The CWA also created a requirement for technology-based effluent limitations ("effluent limit guidelines") for point source discharges. EPA develops these standards for categories of dischargers, based on the performance of pollution control technologies without regard to the conditions of a particular water body receiving the discharges. This approach is intended to establish a basic national discharge standard for all facilities within a category with "Best Available Technology" as an underlying basis. The standard becomes the minimum regulatory requirement in a permit.

If water quality is still impaired for a particular water body after application of technology-based standards to an NPDES permit, the permitting agency (state or EPA) must add water quality-based limitations to that permit. The additional limitations are to be more stringent than the technology-based limitations and would require the entity that received the permit to meet those additional limitations. Such water quality standards (WQS) set site-specific allowable pollutant levels for individual water bodies, such as rivers, lakes, streams and wetlands. States set WQS by designating uses for the water body (e.g., recreation, water supply, aquatic life, agriculture) and applying water quality criteria (numerical pollutant standards and narrative standards)[16] to protect the designated uses. An antidegradation (in some states referred to as nondegradation) policy is also issued by each state to maintain and protect existing uses and high-quality waters. The development of WQS is a complex process, both scientifically and legally, and tends to be a resource-intensive process for state agencies. The EPA retains oversight authority with regard to state-administered NPDES programs and state-established water quality standards. EPA can override state permit decisions (under CWA section 402(d)) and disapprove state WQS (under CWA section 303(c)).

To date, effluent guideline regulations have been published for 56 categories of pollutants (450 subcategories), covering more than 60,000 facilities that discharge directly or indirectly to the nation's waters. EPA has updated some categories since their initial promulgation and has added new categories. EPA did not consider CBM production in developing the 1979 national technology-based effluent limitations guidelines (ELGs) for the Onshore and Agricultural and Wildlife Water Use Subcategories of the Oil and Gas Extraction Point Source Category (40 CFR 435, Subparts C and E) because no significant CBM production existed in 1979. Accordingly, these ELGs do not apply to CBM produced water discharges. EPA has made the determination that CBM extraction operations are a potential new subcategory of the Oil and Gas Extraction category, but to date no specific

[15] See www.nmenv.state.nm.us/swqb/NPDES/index.html (accessed March 4, 2010).

[16] Narrative standards provide broad-scale, general guidance of a qualitative nature, whereas numerical standards provide specificity in a quantifiable manner. Narrative standards define the broad guidelines that serve as the basis for definition of numerical standards. See waterquality.montana.edu/docs/methane/standards.shtml (accessed March 4, 2010).

requirements have been promulgated for CBM extraction operations. Current NPDES permits involving such discharges must include effluent limitations that are based on the best professional judgment of the permit issuer (whether EPA or the State). The purpose of these limits is to ensure compliance with WQS. The Montana Department of Environmental Quality, for example, under the guidance and directive of the EPA Region 8, has now established technology-based effluent limitations (TBEL) for any new CBM produced water NPDES permits (managed for the EPA by Montana and called Montana PDES, or MPDES) and technology-based effluent limitations will be applied to any permits up for renewal.

CBM operators are required to provide estimates or projections of produced water discharge volumes as part of the NPDES permit application process (or the corresponding state process if the authority is delegated to the state, see below). The estimated or projected produced water discharge volumes are reported in the permit application as a maximum volume (i.e. as "up to" a given volume, measured in million gallons per day, barrels per day, acre feet per year, or other units). The permitted discharge is typically associated with a pod of wells and water production per well (at the well-head) is not generally determinable—since water from multiple wells is comingled in a single pipeline before discharge (see also Chapter 4). No in-line flow monitoring and no end-of-pipe continuous or real-time monitoring of flow is required, once a permit is issued. CBM operators are not normally required to monitor discharge volumes except as instantaneous values or measures at a moment in time on either a monthly, quarterly, or semi-annual basis essentially to fulfill reporting requirements. CBM operators are typically required to monitor and report on an infrequent, but fixed schedule. Real-time discharge volumes and water quality concentrations can vary significantly over the course of a given year leading to variability in extrapolation or application of these measurements which is important to recognize. Another consideration applied to all live (perennial) water bodies to which discharges are permitted by NPDES is that of the "mixing zone" (Box 3.1).

The Northern Cheyenne in Montana have recently begun the process of establishing their own water quality standards to protect public health and welfare, and enhance water quality to serve the purposes of the CWA. The tribe does not yet have the water quality standards approved by EPA and is entering into a public comment period for the proposed standards at the time of this writing (see also Appendix F). The state of Montana, as noted above, is also presently engaged in a process of defining discharge limitations for a CBM produced water discharge permit using TBEL. Little agreement is established among state regulatory agencies, the EPA, industry representatives, and landowners as to what these limits should be. The limits can vary from state to state, from designated water resource use to water resource use, and from permit to permit within a state (see individual state descriptions below). EPA is currently in the process of evaluating whether to conduct a

BOX 3.1
Mixing Zone

The mixing zone is representative of the downstream portion of a receiving stream (below the NPDES discharge point) where discharge is mixed with ambient flow. Mixing zones can be and in many cases are considerations of significance in determining discharge permit allowances to water bodies. In the case of ephemeral streams, the mixing zone is considered non-existent. Consideration is given to the ambient flow and quality, the discharged flow and quality, and the resulting water quantity and quality at the terminus of the mixing zone. The combination of these conditions and the presence of other discharges in the reach dictate the allowable discharge concentrations. In reality, mixing zone considerations are of much more significance on smaller streams than on large streams and rivers such as the Tongue and Powder rivers because the latter provide much greater opportunity for mixing and dilution.

rulemaking to potentially revise the Oil and Gas Extraction effluent guideline to include specific limits for CBM extraction operations (see Box 3.2).

Safe Drinking Water Act

The SDWA is the principal federal law in the United States that ensures safe drinking water for the public. In accordance with the act, EPA is required to set standards for drinking water quality and to oversee all states, localities, and water suppliers that implement these standards. The SDWA also regulates the construction, operation, permitting, and closure of injection wells that place fluids underground for storage or disposal under its UIC program. Thus, the SDWA governs the reinjection of produced waters from the CBM extraction process. For the most part, states have been delegated primacy of the UIC program. EPA remains responsible for issuing permits in states that have not been delegated primacy for the UIC program and on most tribal lands. Of the six states considered in this study, the EPA has delegated primacy for UIC permits to North Dakota, Wyoming, Utah, and New Mexico, and the EPA shares authority for issuing UIC permits with Colorado and Montana.[17] In applying for a UIC permit, developers must demonstrate that the injection operation will not endanger any underground drinking water source. EPA has maintained oversight for permitting CBM produced water injection by subsurface drip (which requires a UIC permit; see Chapter 4 for description of these management methods).

Five classes of injection wells are allowed under this regulatory scheme. Wells are classified by type of fluid injected and the specific location where the fluid is to be injected (e.g.,

[17]See www.epa.gov/ogwdw000/uic/primacy.html (accessed March 4, 2010).

BOX 3.2
EPA's Detailed Study of the CBM Extraction Sector Under the CWA

The CWA requires the EPA to review its effluent limit guidelines annually to determine if amendments might be appropriate to existing regulations. In cases where an amendment is being considered, the EPA first conducts a screening-level review to identify effluent categories needing further characterization. Candidates for potential review are then prioritized based on various factors such as industrial categories, pollutant discharges, and economic considerations. Pending the outcome of the screening and prioritization, a particular industry sector and/or pollutant category may undergo an in-depth, detailed review prior to any decision being made with regard to amending the CWA regulations. At various stages of this process, EPA results are published and open for public comment.

Motivated by the growth of the CBM extraction industry and the potential impacts to surface waters from discharge of CBM produced water, the EPA began considering the potential to designate CBM extraction as a specific subcategory with its own guidelines under the Oil and Gas Effluent category of the CWA. A "detailed study" of the CBM extraction industry was therefore recently begun by EPA to consider the possibility of recommending such a designation for the CBM industry.

The objective of the study for CBM extraction is to evaluate the potential environmental issues associated with the discharge of CBM produced water. The study is national in scope, with each CBM basin being considered separately with respect to potential pollutants in produced water discharges and water volumes.

The work plan for the detailed study includes conducting industry surveys to collect technical, economic, and environmental data from a wide range of CBM operations across the United States; site visits and collection of ancillary data from other sources such as the Energy Information Agency; and conducting stakeholder meetings in the major CBM basins. The EPA received approval from the Office of Management and Budget to distribute the mandatory survey for the detailed study in February 2009, at which time EPA distributed a screener questionnaire. Approximately 290 operators with three or more CBM wells received the questionnaire. A detailed questionnaire was distributed to approximately 250 CBM projects in October 2009. EPA will analyze the survey results from the detailed questionnaire and identify whether to initiate a rulemaking in the final 2010 Effluent Guidelines Program Plan. To date, EPA has contacted over 700 people in eight states in over 70 outreach and data collection activities since 2007 in connection with this activity. The results of the detailed study were not available at the time of the writing of the present report.

More information about effluent guideline limits under the CWA can be found at www.epa.gov/guide/304m/ (accessed March 4, 2010). Information specific to the coalbed methane extraction detailed study can be found at water.epa.gov/scitech/wastetech/guide/cbm_index.cfm (accessed August 23, 2010).

SOURCE: Johnston (2009).

below sources of drinking water). Under this program, oil and gas industry injection wells are generally regulated as Class II injection wells, which also generally cover enhanced oil recovery projects or projects involving the disposal of nonhazardous exploration and production wastes. An explanation of the distinction among classes of wells regulated under the SDWA is provided in Table 3.2. Regulatory authority for these types of wells is sometimes

TABLE 3.2 Classes of Wells in the EPA UIC Program

Class	Use
I	Injection of hazardous wastes, industrial nonhazardous liquids, or municipal wastewater beneath the lowermost underground sources of drinking water (USDWs) (549 wells).
II	Injection of brines and other fluids associated with oil and gas production and hydrocarbons for storage. Injected beneath the lowermost USDWs[a] (143,941 wells).
III	Injection of fluids associated with solution mining of minerals beneath the lowermost USDW (18,505 wells).
IV	Injection of hazardous or radioactive wastes into or above USDWs. Banned wells unless authorized by federal or state groundwater remediation project (32 sites).
V	All injection wells not included in Classes I–IV. Generally used to inject nonhazardous fluids into or above USDWs and typically shallow onsite disposal systems.

[a]The table provided by EPA describes Class II wells as "injected below the lowermost USDW." Although this may be correct in most cases, injection below the lowermost USDW is not required for Class II wells, according to UIC regulations.

NOTE: Class II wells are the most common of five classes of UIC wells used in the United States and include wells used for deep-well injection of CBM produced water, as well as for injection of brines remaining after water treatment (see also Chapter 6).

SOURCE: Available at www.epa.gov/ogwdw000/uic/wells.html (accessed March 4, 2010). See also www.access.gpo.gov/nara/cfr/waisidx_02/40cfr144_02.html (accessed June 21, 2010).

delegated to oil and gas conservation commissions or equivalent agencies within each state (see also Table 3.1). With CBM, most reinjection of produced water is done into Class II wells although in Wyoming, a large percentage of reinjection is into Class V wells.

In addition to specific regulations associated with surface and underground discharges, EPA Region 8 has recommended guidelines for off-channel, unlined CBM impoundments to prevent impacts to surface water, high-quality shallow groundwater, domestic wells, and stock wells (EPA, 2002a, 2002b) which were developed by Wyoming Department of Environmental Quality (DEQ) in 2002.[18] The guidelines include siting impoundments at distance from floodplains, terraces, and ephemeral channels and over thick unsaturated soil and geological materials (>50 feet) to minimize water flow from beneath impoundments. The guidelines also recommend that a clear description be provided of the data needed to evaluate potential impacts to groundwater, including downgradient surface water and

[18]See www.epa.gov/region8/ (accessed March 4, 2010).

groundwater monitoring to help determine the degree of hydrological connection, if any, between the impoundment and surface water (EPA, 2002a, 2002b).

WESTERN STATE AUTHORITIES

The six western states included in this study have varying approaches to produced water management. Water quality standards being applied to management of produced water may be narrative or numeric. Agencies have greater latitude in translating narrative criteria to permit limits for CBM produced water discharge and enforcement of provisions of discharge than with numeric criteria. State-specific approaches for regulating CBM produced water for the five states that presently have active CBM development are described below with respect to water rights issuance, CBM production permitting, and CBM water management. Produced water management for conventional oil and gas operations is described for North Dakota, where no CBM production presently occurs. The states are presented in a general geographical and geological sequence, which groups states that produce CBM from shared basins; this presentation order is designed to facilitate comparison of produced water management approaches between states that may share CBM basins with similar geological and hydrogeological conditions. North Dakota is described first, followed by Montana and Wyoming (with the shared Powder River Basin), Utah and Colorado (which share basin similarities in the Uinta and Piceance), and New Mexico (which shares the San Juan and Raton basins with Colorado).

North Dakota

The North Dakota State Water Commission, through the Office of the State Engineer, oversees issues related to water rights. The North Dakota Department of Health's Environmental Health Section administers the state's water quality rules and regulations, reviews and issues NPDES permits for surface discharges, and administers the UIC program for the state, with exception of Class II injection wells, which are overseen by the North Dakota Industrial Commission, through its Oil and Gas Division (Table 3.1). The latter agency also has jurisdiction over oil and gas exploration and production permits on state and private lands. Although no CBM production has yet occurred in North Dakota (EIA, 2009), management options for produced water from conventional oil and gas operations are described here for completeness.

The North Dakota Source Water Protection Program, developed in the late 1990s and approved by the EPA, is an umbrella under which North Dakota fulfills the provisions of the SDWA.[19] A primary goal of the program is to prevent the contamination of public

[19]See www.ndhealth.gov/WQ/GW/sourcewater.htm (accessed March 4, 2010).

water supplies, including surface water and groundwater sources (Table 3.1). The program includes designating a well head protection area for groundwater-dependent public water systems, or a source water protection area for surface-water-dependent public water systems. Both numerical and narrative standards are established to preserve the state's water resources (Schafer and Sagsveen, 1999).

Underground injection, disposal to surface waters, and disposal to the ground are the primary management options in the state, with respect to produced water management from oil and gas production activities. Any saltwater liquids or brines produced during oil and gas operations are considered wastes and are required to be processed and disposed of in ways that do not pollute freshwater supplies and are not allowed to pool on the surface or infiltrate the soil. Although beneficial uses for produced water are recognized by the state (Table 3.1), reinjection is the preferred method of disposal for 96 percent of all produced water from conventional oil and gas operations (Clark and Veil, 2009). Discharge to surface waters is permitted only if the discharge does not endanger public health or degrade water quality. Surface facilities for disposal of produced water are acceptable primarily in storage tanks constructed of materials resistant to the effects of saltwater liquids, brines, or chemicals. Open ponds and pits are generally allowed only through special approval or in the case of an emergency (NDIC, 2006).

Montana

Montana is the only state in the West that addresses CBM produced water directly in its statutes, with several state agencies responsible for various aspects of CBM development and produced water management on state- and privately owned lands. The Montana Department of Natural Resources and Conservation (DNRC) oversees issues of water rights, the Montana DEQ oversees surface discharges through MPDES, and the Montana Board of Oil and Gas Conservation oversees oil and gas operations, including those for CBM, and has been delegated jurisdiction by EPA over the UIC program for Class II wells (see Table 3.1).[20]

The specification for CBM activities and produced water statutes in Montana stems from an order in 1999 when the DNRC created the Powder River Basin groundwater area for private and state land (but not tribal land). In addition to allowing for reduction of water levels in targeted aquifers near CBM project areas, this order included the need for monitoring water resources before, during, and after CBM production. The order also includes a requirement for the CBM operator to offer mitigation agreements to owners of wells or springs that may be impacted by CBM activities.[21]

[20]See bogc.dnrc.state.mt.us/BoardSummaries.asp (accessed March 4, 2010).
[21]See www.bogc.dnrc.state.mt.us/CbmOrder.htm (accessed March 4, 2010).

In 2003 the Montana Board of Environmental Review (BER) adopted numerical standards to regulate water quality in the Powder River Basin for electrical conductivity (EC) as a surrogate for total dissolved solids) and sodium adsorption ratio (SAR), specifically because EC and SAR can impair the usefulness of water for irrigation (see also Chapters 2, 4, and 5). The standards were based on agricultural use of the receiving waters for irrigation as the designated beneficial use to be protected. For discharge of CBM produced water to other basins, a narrative standard was approved (Montana DEQ, 2003). The EPA approved the numerical standards as enforceable under the CWA and within the Powder River Basin, which transcends the Montana-Wyoming border. Thus, under EPA regulations, point source discharge permits issued or authorized by Wyoming to waters in Wyoming and upstream from Montana must meet Montana water quality standards for the Tongue and Powder rivers, which flow northward into Montana from Wyoming. This assurance of water quality standards includes the tributaries to the Tongue and Powder rivers and is considered particularly important for purposes of irrigation by farmers and ranchers in southeastern Montana.[22]

In 2006 the Montana BER appended "nondegradation" provisions (also referred to as antidegradation provisions) to the numerical standards for salinity and sodicity of the Tongue and Powder Rivers and tributaries. In essence, the nondegradation provisions indicate that significant degradation of high-quality waters of the state is not allowable either by (1) significantly elevating the instream salinity or SAR above the mean ambient concentration or (2) causing an increase in instream salinity or sodicity amounting to 10 percent or more of the numerical standards (Montana DEQ, 2006).

Since the 2003 ruling and the subsequent 2006 nondegradation provisions, Montana has been involved in numerous related lawsuits. A number of oil and gas companies operating in Montana and Wyoming have filed suit to overturn EPA's approval of the 2003 numerical water quality standards and to mandate that EPA disapprove the 2006 nondegradation provisions. The state of Wyoming intervened on the side of the companies. Challenges to Montana's 2003 and 2006 water quality standards for EC and SAR have been successfully defended in the Montana Supreme Court and are in effect under Montana state law.[23] A subsequent EPA Region 8 approval of the Montana standards was remanded by a federal district court back to the EPA, due to inappropriate processes followed by EPA for approval. Public comment is now being solicited regarding the proposed standards, after which EPA will likely respond and proceed with the approval process.

By negotiated agreement in some common water basins, Wyoming water sources are required to comply with Montana standards (see also, below, under Wyoming). The water quality standards to which Wyoming has agreed are the numeric water quality standards

[22]See www.doj.mt.gov/lands/waterrights.asp (accessed March 4, 2010).
[23]Ibid.

for EC and SAR adopted by the Montana Board of Environmental Review, as applied to the Tongue and Powder Rivers and their tributaries.

Under Montana code, waste and contamination of groundwater is prohibited, except in specific cases, such as "the management, discharge, or reinjection of ground water produced in association with a coal bed methane well."[24] Until only recently, CBM operators in Montana had three primary approaches by which to dispose of their CBM produced water: (1) use of the water for irrigation, livestock watering, or other beneficial uses (see Table 3.1); (2) approved UIC reinjection of the water into acceptable rock formations; or (3) discharge of the water to surface waters or impoundments with an appropriate MPDES permit.[25] Two recent judicial rulings, each of which challenged the constitutionality (Montana) of either disposal to surface impoundments or discharge of untreated water to surface waters of the state have had significant impact on the third approach. In April 2010, a Montana district judge ruled that the use of evaporation pits for the disposal of CBM produced water is unconstitutional in Montana. In May 2010, the Montana Supreme Court unanimously ruled that CBM operators must treat water that is pumped from underground before discharging the water into Montana's streams and rivers. The court also found that the Montana DEQ violated the federal CWA and the Montana Water Quality Act by issuing methane discharge permits without requiring that the water be treated before release.

Wyoming

In Wyoming the State Engineer retains jurisdiction over produced water from CBM wells and requires operators to obtain groundwater appropriation permits.[26] The Wyoming DEQ Water Quality Division oversees produced water discharges (NPDES permits administered on behalf of EPA by Wyoming, called WYPDES) and has primacy for regulating UIC permits for Class I, III, and V wells, as well as watershed management and groundwater pollution control.[27] The Wyoming Oil and Gas Conservation Commission is responsible for permitting oil and gas wells, including those for CBM production, as well as UIC permits for Class II reinjection wells (Table 3.1).[28] Horizontal injection for the purposes of underground drip irrigation is also regulated by the Wyoming UIC program as Class V wells.

The primary CBM produced water management options in the state include direct surface discharge, with or without treatment depending on water quality; reinjection (deep-

[24]Montana Code Annotated § 85-2-205; see data.opi.state.mt.us/bills/mca/85/2/85-2-505.htm (accessed March 4, 2010).

[25]Montana Code Annotated § 82-11-175; see data.opi.state.mt.us/bills/mca/82/11/82-11-175.htm (accessed March 4, 2010).

[26]See seo.state.wy.us/ (accessed March 4, 2010).

[27]See deq.state.wy.us/wqd/ (accessed March 4, 2010).

[28]See wogcc.state.wy.us/ (accessed March 4, 2010).

well or shallow drip systems); and disposal into impoundment facilities (pits or reservoirs) (DiRienzo, 2008). Wyoming has established an interagency working group[29] to address issues related to CBM produced water management, including monitoring and protocols.

Generally groundwater appropriation permits for CBM produced water are granted from the State Engineer's Office if a beneficial use is demonstrated (Table 3.1) and if the State Engineer determines that the proposed means of diversion and construction are adequate. An application can be denied if the State Engineer determines that the activity is not in the public interest. The State Engineer's Office considers CBM production different than conventional natural gas production "due to the necessity for production of water for the production of the gas resource" and has designated CBM as a beneficial use of water on this basis. Permits are thus required for appropriation of groundwater (Wyoming SEO, 2004). Groundwater protection with respect to surface discharges into impoundments is monitored under the DEQ Groundwater Pollution Control program (Fischer, 2009),[30] which has had standards and practices in place for groundwater monitoring, reporting, and monitoring well plugging and abandonment.

Unlined surface impoundments require permits in Wyoming by the State Engineer's Office (for reservoirs—"on-channel"[31]) or the Oil and Gas Conservation Commission (for pits—"off-channel"[32]). In addition, the BLM authorizes impoundments on federal lands and issues federal leases for water disposal to such impoundments. Discharge permits to impoundments are required by the Wyoming DEQ under WYPDES; the permits required vary by drainage basin. In some cases, groundwater protection permits are required under the Wyoming Groundwater Pollution Control (GPC) Program. These permits are also issued by the Wyoming DEQ. Monitoring requirements under the GPC program depend on depth to groundwater and water quality beneath the impoundment and the degree of hydrologic connection to surface water. [33]

In April 2010, Wyoming DEQ released a new set of specific guidelines for compliance monitoring and siting requirements for unlined impoundments (on- and off-channel) containing CBM produced water (Wyoming DEQ, 2010). These guidelines supersede

[29]See www.wy.blm.gov/prbgroup/ (accessed May 19, 2010).

[30]See also deq.state.wy.us/wqd/groundwater/index.asp (accessed March 4, 2010).

[31]An "on-channel" (or "in-channel") impoundment that receives CBM produced water is sited within a designated water feature or within the floodplain or alluvium of a water feature. These features include intermittent perennial and ephemeral streams, dry washes, and lakes. Engineering modifications are made to the channel to enhance capacity for temporary or long-term storage of water. An "off-channel" impoundment is not sited within such a designated water feature and is constructed in areas outside of the natural flow path and not directly connected to any direct surface flow paths to pre-existing ephemeral or perennial channels.

[32]An "off-channel" impoundment is not sited within such a designated water feature and is constructed in areas outside of the natural flow path and not directly connected to any direct surface flow paths to pre-existing ephemeral or perennial channels.

[33]D. Fischer, Wyoming DEQ, Personal communication, July 14, 2009.

requirements in previous guidance documents and were revised as a result of a comprehensive review of groundwater compliance monitoring data that the Wyoming DEQ had received since the inception of the monitoring requirements in August 2004. Groundwater monitoring is required because water infiltrating from unlined CBM impoundments has the potential to dissolve in situ minerals and affect the state's groundwater resources. The revised guidelines implemented changes to the existing compliance monitoring program and maintained the siting and subsurface groundwater compliance monitoring requirements prior to new impoundment construction and subsequent to discharge of CBM produced water into the impoundment.

Under WYPDES, the state has established a policy specifically for discharges of CBM produced water to surface waters of the Powder River mainstem to provide assurance that both Wyoming narrative standards and Montana numerical standards for TDS and sodium are met. A key foundation to the policy is management of the "assimilative capacity"[34] of the Powder River. Of the chemical constituents in CBM produced water, TDS and sodium were the only ones identified with sufficient potential to exceed Montana water quality standards at the state line, and the Wyoming DEQ has therefore instituted a greater level of permitting oversight for these two constituents. Wyoming has no numerical standards in place for sodium and Wyoming's existing numerical standards for TDS are not applicable to the protection of irrigation uses of water. Wyoming state officials use the Montana numerical standards for TDS (as a proxy for EC) and SAR (see above) to ensure that discharges into the Powder River do not exceed the assimilative capacity and do not degrade designated uses of surface waters (Wyoming DEQ, 2006).

Utah

Under Utah law, administration of the appropriation and distribution of the state's water resources rests with the Utah Division of Water Rights (DWRi), led by the state engineer within the Utah Department of Natural Resources (DNR).[35] The Utah DEQ's Division of Water Quality and the Board of Water Quality oversee water quality issues associated with surface water and groundwater of the state[36] and have jurisdiction over the UIC program for Class I, III, IV, and V wells. Specific jurisdiction over CBM development and produced water management rests under the DNR with the Division of Oil, Gas, and

[34] "Assimilative capacity" refers to the capacity of a natural body of water to receive wastewaters or toxic materials without deleterious effects and without damage to aquatic life or humans who consume the water. See www.epa.gov/OCEPAterms/aterms.html (accessed March 4, 2010).

[35] See nrwrt1.nr.state.ut.us/ (accessed March 4, 2010).

[36] See www.waterquality.utah.gov/DWQ_info.htm (accessed March 4, 2010).

Mining (DOGM) and its policymaking body, the Utah Board of Oil, Gas, and Mining,[37] which also has primacy for the UIC program for Class II injection wells (Table 3.1).

The operator must take "all reasonable precautions" to avoid polluting lands, reservoirs, natural drainage ways, and groundwater sources. With respect to CBM operations, produced water is generally considered by Utah to be a "byproduct" of oil and gas production, thus falling under the jurisdiction of the DOGM. Such produced water must be disposed of in compliance with all applicable state, federal, or local regulations. However, in some circumstances the State Engineer's Office may authorize temporary water rights to allow produced waters from mining operations (including CBM produced water) to be put to beneficial use once it has been diverted from its underground location (Bryner, 2002). Because much of Utah is closed to new appropriations of water, new projects and allocations require acquisition and amendment of existing rights for new purposes (BLM, 2001b).

Most CBM produced water in Utah is not potable without treatment and is disposed of by reinjection into subsurface formations. Operators may choose to dispose of produced waters via subsurface injection in Class II wells under the state UIC program (Bryner, 2002). Although state regulations do not specifically address CBM produced waters, the DOGM has rules that address the disposal of "saltwater and oil field wastes," which include CBM produced water.

As of November 2009, the Utah Administrative Code set out the permitting rules for lined and unlined wastewater disposal pits (Rule R6949-9, Waste Management and Disposal).[38] The rules describe various requirements for wastewater disposal pits, both lined and unlined, including geological and hydrogeological constraints for locating the pits; parameters for the type and thickness of the lining for lined pits; testing subsurface conditions prior to construction; climate considerations (to gauge, for example, evaporation and precipitation in the location of the pit); the daily water quantity to be disposed of, and water quality analyses, including the chemical constituents of the produced water relative to local groundwater. Disposal of CBM produced water in an unlined impoundment may be permitted by the DOGM if the disposal does not demonstrate pollution potential to surface or groundwater and that the disposal meets one or more of the following criteria: (1) the produced water does not have TDS in excess of local groundwater and does not contain objectionable levels of chlorides, certain organic compounds, or sulfates; (2) most or all of the water is to be used for beneficial purposes such as irrigation, livestock or wildlife watering and produced water analysis indicates that the water is appropriate for the intended use; and/or (3) the volume of produced water to be disposed is less than 5 barrels per day per month. If beneficial use is the basis for the application for an unlined pit, written confirmation from the users should also be submitted. The responsibility for conducting the

[37]See ogm.utah.gov/ (accessed March 4, 2010).

[38]See www.rules.utah.gov/publicat/code/r649/r649-009.htm#T3 (accessed March 4, 2010).

analyses for permit applications and for subsequent compliance for disposal impoundments lies with the permit applicant.

Colorado

The Office of the State Engineer (Division of Water Resources [DWR]) of the Colorado Department of Natural Resources administers the diversion and use of surface waters and groundwater of the state, including groundwater withdrawal for beneficial use (see Table 3.1). The Colorado Department of Public Health and Environment Water Quality Control Division (WQCD) has authority over environmental laws related to waste discharges to surface waters, including produced water from CBM operations.[39] The Colorado Oil and Gas Conservation Commission (COGCC) is the primary state regulatory authority over oil and gas activities in the state and until recently maintained jurisdiction over produced water from CBM operations under the state standards established for general oil and gas exploration and production. The COGCC generally has considered produced water to be a byproduct and defined it as a "waste" from exploration and production under Rule 907 (Rein, 2009; Stednick et al., 2010). Under this definition, CBM operators have thus not been required to obtain a permit from the Office of the State Engineer to withdraw the produced water since it was a "waste product" of the methane extraction process.

COGCC's Rule 907 describes how produced water should be managed and disposed of: (1) subsurface reinjection via a Class II injection well; (2) evaporation or percolation in a lined or unlined pit; (3) disposal at a commercial facility; (4) disposal via surface discharge through road spreading (outside sensitive areas); (5) discharge into waters of the state (under rules of the WQCD); (6) reuse of the water for enhanced recovery, recycling, or drilling; and (7) treatment to be used as an alternate domestic water supply to surface owners within the oil and gas field (Rein, 2009). Permits through the COGCC (or the WQCD for surface water discharge) are required before an operator may employ any of these disposal methods. As outlined below, the classification of CBM produced water for purposes of regulation changed in the state in 2009 and has implications for industry and for authorities regulating CBM operations and produced water.

Beneficial use of produced water from a CBM well by the operator or another person requires compliance with the water rights acts of the state and requires a water well permit, issued by the State Engineer. A well permit for water from a CBM well presumes that the water is tributary, although the person may submit data to document that the water is nontributary (Wolfe and Graham, 2002).[40] Nontributary water is essentially water that is considered isolated, or compartmentalized, with respect to surface water so that its diver-

[39]See www.netl.doe.gov/technologies/pwmis/regs/state/colorado/index.html (accessed March 4, 2010).

[40]In a nontributary aquifer a proposed diversion will not deplete surface streams more than 0.1 percent of the proposed diversion volume in any year for up to 100 years (Rein, 2009).

sion would have little impact on surface water. In contrast, tributary water is water that contributes flow to surface water and therefore impacts senior water rights on the surface water. A water well permit for tributary water use would have to address senior surface water rights (under the prior appropriation doctrines) and require approval of an augmentation plan in Colorado water court (Rein, 2009).

Recently, the entire landscape regarding Colorado's regulation of CBM operations and produced water was overturned in *Vance et al. v. Wolfe* by the Colorado Supreme Court whose decision can have broad implications for oil and gas producers in the state. In April 2009 the Court ruled that extraction of tributary groundwater produced from CBM wells is a "beneficial use" of water that must be regulated under state water laws. The decision also determined that CBM wells producing tributary groundwater are, in effect, water wells that require well permits issued by the State Engineer and, where applicable, these wells may also require a court-approved plan (an augmentation plan) to replace out-of-priority depletions to impacted stream systems.

Vance involves the appeal of a declaratory judgment issued by the Water Court for Water Division 7, which has jurisdiction over all "water matters" in the San Juan River Basin in southwestern Colorado. The plaintiffs were ranchers and landowners who own surface water rights in the basin, which they claimed could be impacted by water withdrawals related to CBM production.

In affirming the Water Court's decision, the Colorado Supreme Court in *Vance* ruled that extraction of water through CBM wells constitutes beneficial use and an appropriation of water; thus, CBM wells that produce tributary water are subject to water well permitting, water court adjudication, and administration in Colorado's water rights priority system. In so ruling, the court expressly declined to give deference to the State Engineer's long-standing policy of refusing to regulate produced water on the grounds that it is a waste product subject only to the jurisdiction of the COGCC (Colorado Supreme Court, 2009).

To deal with the implications of *Vance*, the Colorado General Assembly passed House Bill 09-1303, which would provide an orderly process for bringing CBM wells that produce tributary groundwater into the state's well permitting and water rights administration system. Under the legislation, operators of CBM wells that produce tributary groundwater will be required to obtain well permits and administrative approval of plans to replace depletions caused by well pumping, no later than March 31, 2010. Operators will be required to file applications with the water court for approval of long-term "plans for augmentation" no later than December 31, 2012. The legislation also authorizes the State Engineer to adopt rules to assist with regulation of the production of nontributary groundwater by delineating areas of nontributary groundwater withdrawal. If produced CBM water can be shown to be nontributary, the need for water well permitting and an augmentation plan can be avoided for a CBM well and its produced water (Rein, 2009).

New Mexico

The Office of the State Engineer for New Mexico has jurisdiction over the supervision, measurement, appropriation, and distribution of all surface water and groundwater resources in New Mexico. Under New Mexico law, all ground- and surface waters belong to the public and are subject to appropriation under the Doctrine of Prior Appropriation.[41] However, the State Engineer has no authority over aquifers containing nonpotable water located 2,500 feet or more below the land surface. In New Mexico most CBM wells fall under this provision and are, therefore, not permitted by the State Engineer (New Mexico Legislature, 2009).[42]

The New Mexico Environment Department (NMED) oversees the main environmental protection laws for the state, including surface water quality through NPDES permits and issues related to watershed protection.[43] The Water Quality Control Commission (WQCC), an administrative part of the NMED, has responsibility for enforcing the Water Quality Act and delegates authority for enforcing certain regulations under this act to the Oil Conservation Division (OCD).[44]

The OCD of the New Mexico Department of Energy, Minerals, and Natural Resources, under the New Mexico Oil and Gas Act, administers "water produced or used in connection with the drilling for or production of oil and gas" and may regulate surface or subsurface disposal of produced water to protect freshwater sources (New Mexico SWQB, 2000). CBM produced water is not explicitly regulated by existing state regulations but is included under the provisions of the Act. Approved disposal methods for produced water include lined pits, below-grade storage tanks, and treatment and discharge for beneficial uses. As of 1993, unlined pits were prohibited by state law. The OCD regulates subsurface injection of produced water in Class II wells and is the lead agency for the UIC program for the state, because most injection wells in New Mexico are associated with oil and gas production; 99 percent of CBM produced water in the state is managed by deep-injection wells. The OCD also performs groundwater monitoring to carry out responsibilities delegated to it by the WQCC and to ensure reasonable protection of fresh water as required by the New Mexico Oil and Gas Act (New Mexico SWQB, 2000).

CHAPTER SUMMARY

The requirements associated with leasing and permitting CBM operations on federal and tribal lands through BLM and protecting water resources on federal, state, tribal, or

[41]See www.ose.state.nm.us/ (accessed March 4, 2010).
[42]M. Fesmire, presentation to the committee, June 2, 2009.
[43]See www.nmenv.state.nm.us/SWQB/ (accessed March 4, 2010).
[44]See www.netl.doe.gov/technologies/PWMIS/regs/state/newmexico/index.html (accessed March 4, 2010).

private lands through the CWA and SDWA under EPA's jurisdiction are relatively broad but clear. USFS is responsible for surface resource management on national forest system lands and works in conjunction with the BLM, which maintains statutory responsibility for issuing and supervising leases on these lands. On tribal lands, the BIA authorizes energy leases and the BLM permits CBM operations in a way that is similar to federal leases. Specific provisions under the NPDES permitting process apply to disposal of produced waters to the surface. The UIC program, under the SDWA, applies if subsurface reinjection of produced water is the disposal method. Federal agencies work in concert with state and tribal authorities to enforce federal standards and regulations, and EPA has delegated primacy for some of these permitting and regulatory functions to relevant state and tribal authorities in the six western states examined in this study.

Under the provisions of both the CWA and the SDWA, states and tribes assuming primacy for implementation of provisions of the terms of these acts commit to implementing appropriate state or federal laws and policies that serve to protect and preserve clean and safe surface and groundwater resources within the boundaries of the respective states. States and tribes may seek to establish their own water quality standards to serve the purposes of the CWA.

Similarities among the six western states' approaches to produced water management, including CBM produced water where applicable, include provisions for appropriate siting, construction, and lining of impoundments. However, significant differences exist in the management of CBM produced water among states to fulfill the general tenets for preservation of clean and safe water resources. From a legal standpoint, a deciding factor for states in their approach toward CBM produced water management relates to whether the water is considered an undesirable waste or, in other cases, a resource that can be beneficially used. A second important factor is that only Montana, and to a lesser extent Wyoming and Colorado, have specific provisions for CBM produced waters in their existing state regulations.

Important perspectives also relate to the approaches taken by various Native American tribes with lands within or adjacent to basins with active CBM development. Several tribes have active CBM production on their lands and manage CBM produced water. Other tribes have been evaluating the potential to produce CBM on their lands and are in the process of developing new water quality regulations to mitigate potential impacts of CBM produced water disposed of in rivers that flow through their lands.

Because all waters are owned by someone or some entity, in cases where the production of water is a byproduct of CBM production and where the waters are owned by an entity not party to the oil and gas lease, the leases often explicitly state that the waters may not be put to beneficial use unless the owner of the water approves. Thus, existing water laws preclude a CBM gas developer from taking possession of the water by means of filing for a water right. The CBM operator is assigned responsibility for dealing with the produced water as a waste product, but cannot market the water or transfer a water right. In this sense, existing water laws do not encourage beneficial use of CBM produced water.

This designation by states of produced water, generally, as a waste or with potential for beneficial use is not entirely arbitrary, as it has some basis in the general quality of the produced water, which itself is dependent on various hydrogeological factors of the basin and climate and available use options in the state. Nonetheless, other factors are important to take into consideration as new policies for water management are discussed and proposed or enacted. These factors include produced water volumes, available technologies and costs for treating produced water (Chapters 4 and 6), and detailed analysis and documentation of the type of groundwater reservoir—whether confined from (nontributary) or connected to (tributary) surface water—from which the produced water was extracted.

Recent changes, for example, in the case of Colorado court decisions regarding the "tributary" nature of produced water, and ongoing litigation related to Montana's challenge to Wyoming over priority water rights of the Powder River (and the need to honor state-instituted water quality standards at the state boundary), exemplify state-specific approaches about how produced water is perceived and the realization of a need for change in perspectives on water resource management. These changes and consequent actions signal that both the legal system and government agencies recognize that water resources to traverse state, legal, and geological boundaries. Less well recognized is the idea that some water resources can remain static or confined in the subsurface for millions of years until disturbed by human activity—and fossil water is not a concept that is integrated in the current federal or state systems for managing water resources. Emerging case law applied to CBM produced water management is testing the regulatory framework associated with water resources.

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CHAPTER FOUR

Coalbed Methane Produced Water Management and Beneficial Uses

Coalbed methane (CBM) produced water can be managed as a waste product or put to beneficial use, depending on water quality and quantity, legal and regulatory issues, permitting constraints for discharge and use, the local environment and climate, and economic considerations. This chapter addresses the management of CBM produced water, including options for beneficial use, and provides context for Chapter 5, which addresses effects of CBM produced water on the environment. Chapter 6 reviews specific water treatment options and associated costs for managing CBM produced water.

OPTIONS FOR CBM PRODUCED WATER MANAGEMENT

CBM produced water management includes (1) disposal, storage, or treatment as a waste product of methane recovery or (2) application in one of many beneficial use opportunities, with or without treatment. Several factors, alone or in combination, determine whether CBM produced water is disposed of, stored, treated, and/or put to beneficial use:

- Produced water quality;
- Produced water volumes;
- Reliability of assurances of sustained supply over time;
- Proximity of location of produced water in sufficient quantities for beneficial use (such as irrigation) to suitable land parcels;
- Degree of compatibility between produced water quality and potential receiving landscapes, irrigable land parcels, and receiving water bodies;
- Availability of suitable storage and disposal sites;
- Legal or regulatory factors concerning the discharge, management, and use of CBM produced water;

- Economics of storage and disposal versus options for treatment and beneficial use; and
- Concern on the part of the CBM operator over liability associated with produced water management, including water use, discharge, and transfer.

Commercially available water treatment techniques can be employed individually or in combination to attain the water quality to support *any* beneficial use, but at variable costs (Veil, 2009; see Chapter 6).[1] Disposal and storage options include direct discharge to surface water bodies (depending on produced water quality and quantity and relevant regulations), deep- or shallow-well reinjection and/or storage in surface impoundments, evaporation, and land application. Table 4.1 summarizes the strategies used to manage produced water in the western CBM-producing basins.

Two broadly contrasting approaches to produced water management are highlighted in this chapter: (1) the Powder River Basin, where substantial water volumes and relatively low salinity have yielded a variety of options for eventual use of treated or untreated CBM produced water, and (2) the San Juan Basin, where low water volumes and relatively high CBM produced water salinity have made deep-well injection of untreated produced water a standard practice (see Table 2.1; Table 2.2).

The volume of water produced annually from Powder River Basin CBM wells is substantially greater than that of any other western basin (see Chapter 2 and Table 2.1). The large number of wells with high water production from relatively shallow depths has thus focused much of the attention regarding management of CBM produced water and its impacts on this basin, particularly the Wyoming portion of the basin where most CBM production currently occurs (Box 4.1). However, as outlined in Chapter 3, within each of the CBM producing basins where water is being brought to the land surface, volume is not the only factor taken into consideration in the context of produced water management. State natural resource and regulatory agency statutes and administrative rules, in addition to U.S. Environmental Protection Agency (EPA) permitting requirements for disposal or beneficial use application, dictate or regulate which disposal and management strategies may be employed by the operators and water management contractors.

Existing infrastructure, transportation costs associated with shipment of water, and the present-day value of water all influence the extent to which either treated or untreated CBM produced water is perceived or used as a resource. Because the vast majority of CBM produced water is managed by disposal and storage, very little is currently treated for beneficial use. A large majority of the treatment is completed as a requirement for permitted disposal by discharge to surface water.

[1]T. Olson and D. Beagle, Exterran Water Management Services, personal communication, August 4, 2009.

TABLE 4.1 Summary of Primary CBM Produced Water Management Strategies in Western Basins

Basin	Primary Water Management Method	Reference
San Juan	99.9% reinjected	Bryner (2002)
Uinta	97% reinjected, 3% evaporated	Bryner (2002)
Powder River (Wyoming)	64% surface impoundments, 20% direct discharge to streams, 13% for surface or subsurface irrigation, 3% reinjected	D. Fischer, Presentation to the committee, Denver, CO, March 30, 2009.
Tongue River drainage—of the Powder River (Montana)	61–65% direct discharge to streams, 4–5% industrial dust control, 26–30% for surface and subsurface irrigation, 5% surface impoundments	Calculated from information provided by A. Bobst, Montana Bureau of Mines and Geology, Personal communication, December 21, 2009; T. Reid, Montana Department of Environmental Quality, Personal communication, December 30, 2009; and J. Zupancic, BeneTerra, Inc., Personal communication, December 28, 2009.
Raton (Colorado)	70% direct discharge to streams, 2% surface impoundments, 28% reinjected	Bryner (2002)
Raton (New Mexico)	Nearly 100% reinjected	M. Fesmire, Presentation to the committee, June 2, 2009; data for 2008
Piceance (Colorado)	Nearly 100% reinjected; remainder in evaporation ponds	S.S. Papadopulos & Associates, Inc. (2007); data through 2006

NOTE: North Dakota is not listed in this table because the state does not currently have any CBM production. All permitted discharges to ephemeral and perennial drainages in the Montana portion of the Powder River Basin are located in the Tongue River drainage. The Northern Cheyenne tribe has expressed considerable concern about potential impacts of CBM development and produced water management on water resources of the Tongue River drainage (see also Appendix F). Data for water management in this region were pooled from several different sources collected by the committee, each with different levels of detail. Some percentages are thus presented as ranges to reflect the appropriate level of uncertainty.

Table 4.2 provides a summary of the most typically used water management methods, treatment requirements and challenges, and possible ancillary benefits. The management methods have been separated very generally into two categories: storage and disposal options and beneficial use options. Note that these categories are not mutually exclusive in that storage and disposal options do have a range of potential ancillary benefits and uses. The remainder of the chapter discusses these methods in detail.

BOX 4.1
CBM Produced Water Management in the Powder River Basin

CBM producers in the Wyoming portion of the Powder River Basin store the majority of produced water (about 64 percent) in surface impoundments to allow it to evaporate, to be sprayed into the air to enhance evaporation, or to infiltrate into the shallow subsurface or shallow alluvial aquifers (see figure below; Table 4.1). Twenty percent of the CBM produced water is discharged directly to surface water, either after treatment or without treatment if treatment is not required. Although the CBM produced water in the Powder River Basin generally has the lowest total dissolved solids (TDS) concentrations of all the produced water from the western CBM basins, only 13 percent is put to beneficial use, primarily as managed surface irrigation or subsurface drip irrigation. Use of produced water for subsurface drip irrigation requires an underground injection control (UIC) permit (see Chapter 3), inasmuch as the amount of water applied per unit of land is intentionally controlled to promote drainage below the crop root zone and into shallow alluvial aquifers. Only 3 percent of all Wyoming Powder River Basin CBM produced water is disposed of by deep-well reinjection, which also requires a UIC permit. In the Wyoming portion of the basin, 26 million barrels (3,350 acre-feet) of CBM produced water were reinjected in 2008; over the period from 2000 to 2008, 235 million barrels (30,300 acre-feet) were reinjected. In contrast, in 2008 alone in the Wyoming portion of the basin, nearly 77,000 acre-feet of CBM produced water were discharged into surface impoundments, while approximately 15,400 acre feet were directly applied to identifiable beneficial use for irrigation (including managed surface irrigation and subsurface drip irrigation).

In the Montana portion of the Powder River Basin, the two principal water management methods are permitted discharge and managed surface irrigation. The majority of produced water (61 to 65 percent) from CBM operations is discharged to surface water bodies, as treated discharge (see figure below); a 2010 Montana judicial ruling now prohibits the discharge of any untreated CBM produced water to any state waters. Managed surface irrigation comprises 26 to 30 percent of the discharge, of which 7 percent is apportioned to UIC subsurface drip irrigation. Impoundments are used for only 5 percent of the CBM produced water in Montana, and recently the Montana Supreme Court has declared the use of impoundments for disposal of CBM produced water to be unconstitutional. Industrial use of the water for dust control constitutes the final 4 to 5 percent of the produced water management.

The reason for the differences between the two states regarding the selection of management options for CBM produced water is that Montana currently has only two permitted CBM operations. One of these operations produces more than 95 percent of all produced CBM water in Montana and has a preexisting permit for the discharge of about 61 percent of all its produced water into the Tongue River.

Storage and Disposal Options

Reinjection (Deep-Well Injection)

CBM produced water in the Raton-New Mexico, San Juan, Piceance, and Uinta Basins is almost exclusively reinjected into deep, geologic formations, as a means of disposal (Table 4.1). This approach is used in these basins because of the characteristically high

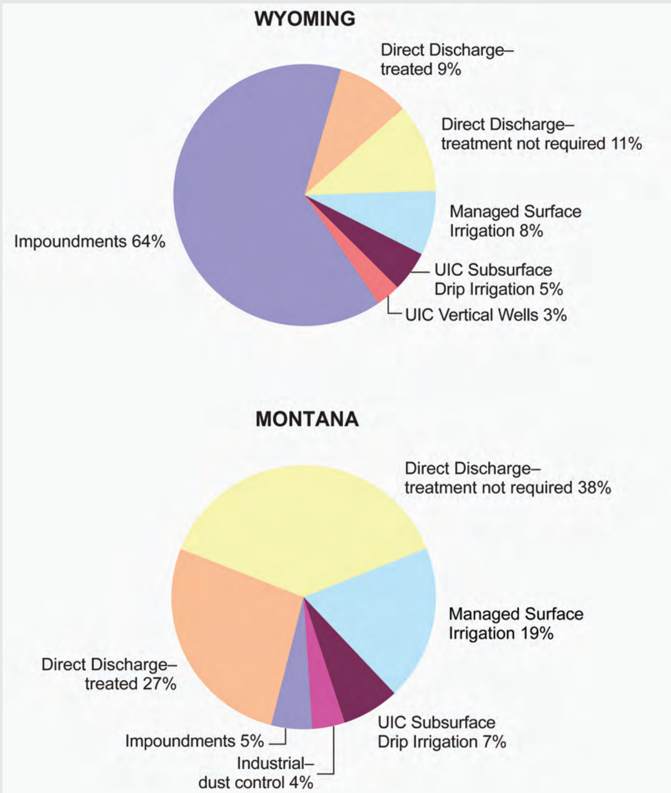

FIGURE Proportional representation of CBM produced water management strategies in the Wyoming and Montana portions of the Powder River Basin. The total amount of water produced in the Wyoming Powder River Basin from CBM extraction in 2008 was approximately 678 million barrels. See also Table 2.1 and Figure 2.8.

SOURCES: Adapted from D. Fischer, presentation to the committee, Denver, CO, March 30, 2009; A. Bobst, Montana Bureau of Mines and Geology, personal communication, December 21, 2009; T. Reid, Montana Department of Environmental Quality, personal communication, December 30, 2009; and J. Zupancic, BeneTerra, Inc., personal communication, December 28, 2009.

NOTE: Chart for Montana correct until May 2010 when the Montana Supreme Court ruled that all CBM produced water must be treated before discharge to Montana streams and rivers.

TDS of the produced water and the relatively low water volume per unit of gas production (Table 2.1; Table 2.2). Geological formations suitable for reinjection in these basins are also well known from historical data associated with water disposal from traditional oil and gas production wells. Treatment by chlorination to address bacterial contamination is required for UIC purposes for deep-well reinjection of CBM produced water. In some cases, filtration of fine particulate material may be required to minimize structural plugging

TABLE 4.2 Commonly Used CBM Produced Water Management Methods, Treatment Requirements and Challenges, and Possible Ancillary Benefits

Management Method	Treatment Requirements and Challenges	Possible Ancillary Benefits
Storage and Disposal Options		
Subsurface (deep-well) reinjection for disposal as Class I, II, or V well	Chlorination is required by the UIC program to addres bacterial contamination	Enhanced hydrocarbon recovery
Subsurface shallow injection for aquifer storage and recovery	May require treatment; dictated by UIC permit requirements; may require chlorination, filtration, pH adjustment	Aquifer replenishment/storage and/or use as drinking water
Discharge to ephemeral and perennial streams	May require none; dictated by NPDES permit requirements; could require salinity, sodicity, fluoride, barium reductions	Flow augmentation, habitat restoration, wildlife and waterfowl habitat
Surface impoundments	Seldom required (Wyoming)	Shallow alluvial aquifer infiltration
Land-applied disposal through water spreading	May require pH adjustment; salinity and SAR reductions; soil amendments to facilitate infiltration	Rangeland habitat improvement, forage production, shallow alluvial aquifer recharge
Beneficial Use Options		
Surface irrigation	Varies from none to pH adjustment, salinity and SAR reductions; soil amendments to facilitate infiltration; ongoing soil quality monitoring	Rangeland habitat restoration, streamflow augmentation, reduced potential for stream dewatering, facilitation of disturbed-lands reclamation (drill sites, coal mining sites, travel corridor reclamation)
Subsurface drip irrigation	Varies from none to degassing, particulate filtration, pH adjustment, salinity and SAR reductions, chlorination for bacterial control; soil amendments to facilitate hydraulic conductivity	Shallow alluvial aquifer recharge, salt leaching, increased crop or forage production

Livestock watering	Dependent on water chemistry, intended duration of impoundment, opportunity for mixing or blending with supplemental water sources. In some circumstances, elective or discretionary treatment of water may be voluntarily imposed to lower salinity, reduce concentration of elements known to be toxic or detrimental to livestock health, particularly trace metals	Wildlife watering, enhanced forage production, enhanced rangeland forage utilization as a result of livestock dispersion and reduced travel distances to water
Instream flow; habitat enhancement: treatment and discharge to streams/wetlands	Dictated by NPDES permit requirements; may require salinity, sodicity, fluoride, barium reductions	Habitat maintenance, restoration, wildlife-waterfowl-fishery habitat, flow augmentation to benefit downstream water users
Municipal/domestic use, aquifer storage	Dependent on water chemistry and desired use, but may require treatment to drinking water standards; chlorination, particle removal filtration	Aquifer storage: future municipal and/or domestic water supply; metal contaminants may adsorb to aquifer and lower dissolved concentrations; less evaporative loss than surface reservoir storage
Industrial use	Varies from no treatment required to reduction of TDS, bicarbonate, and/or other constituents, and temperature and pH adjustment	Reduced demand for withdrawals from existing water supplies

NOTE: NPDES, National Pollutant Discharge Elimination System; SAR, sodium adsorption ratio; TDS, total dissolved solids.

and facilitate reinjection. Shallow well reinjection is not commonly used in these basins for disposal of CBM produced water but may require treatment under UIC permitting requirements.

Although deep-well reinjection is largely used as a disposal method, ancillary benefits may include enhanced hydrocarbon recovery, depending on the formation into which the water is injected, the quality of the produced water, and the water's age (see Box 2.1). Aquifer replenishment and storage may be an ancillary benefit from shallow-well reinjection, again depending on the formation into which the water is injected (see discussion in Chapter 5). The committee did not find any evidence of adverse effects from deep-well reinjection of CBM produced water and did not know of any cases where shallow-well reinjection was used in the Raton-New Mexico, San Juan, Piceance, or Uinta Basins.

Discharge to Ephemeral and Perennial Streams and Surface Impoundments

Recalling that the outfall which discharges CBM produced water into a stream or an impoundment usually represents a combination of CBM produced water combined from several CBM wells (a well "pod") (see also Chapter 3), produced water discharge volumes and concentration of chemical constituents at outfalls may differ from day to day. Treatment of the produced water prior to discharge to either ephemeral or perennial streams or impoundments may also be required to meet permitted discharge requirements.

The only basins where substantial discharge occurs to ephemeral and perennial streams are the Powder River Basin and the Raton Basin of Colorado. Surface discharge is most common at production wells with high volumes of produced water and low concentrations of dissolved solutes (see Chapter 2), although treatment to reduce salinity and other constituents or to manage sodium adsorption ratios (SAR) may be required under the provisions of a state-specific National Pollutant Discharge Elimination System (NPDES) permit. Additional treatment may be required under provisions of an NPDES permit to reduce fluoride, barium, and/or ammonium concentrations. In many instances in the Powder River Basin, little or no treatment is required to meet NPDES standards because of the low levels of most chemical constituents. Some of the ancillary benefits of discharge of produced water to streams, depending on the quality and timing of the flows, include streamflow augmentation, stream habitat restoration, and wildlife and waterfowl habitat enhancement. Although Table 4.2 identifies possible ancillary beneficial uses associated with discharge of CBM produced water to ephemeral or perennial streams, the committee did not find significant evidence or documentation substantiating intentional streamflow augmentation, habitat restoration, or quantified aquifer recharge using CBM produced water.

A substantial majority of the produced water of the Raton Basin in Colorado is currently directly discharged into ephemeral and perennial streams. This practice is due, in part, to the lack of clearly defined regulatory protocols and also because some of the water produced in the Colorado portion of the basin is of relatively low salinity, with low TDS concentrations (see Chapter 2).

A primary mode for disposal of CBM produced water in the Wyoming portion of the Powder River Basin (64 percent of all CBM produced water; Box 4.1) is discharge of untreated CBM produced water into constructed and existing ponds, constructed storage basins, and lined or unlined impoundments. The purpose of impoundments is primarily to facilitate evaporation or infiltration of produced water into the underlying soil. Ancillary benefits of disposal of CBM produced water in impoundments may be livestock or wildlife watering. In numerous instances in Wyoming, evaporation from these impoundments may be enhanced by atomizing or high-pressure spraying of CBM produced water into the atmosphere above impoundments; atomization cannot occur downstream of the impoundment and the atomization process is designed to drain atomized water back into the impoundment. Approximately 3,500 impoundments for storage of CBM produced water have been constructed in the Powder River Basin in Wyoming (Fischer, 2005) (see also Chapter 5 for discussion of documented effects to groundwater beneath impoundments). The use of impoundments in other basins is negligible or nonexistent except for temporary storage prior to deep-well reinjection.

During the first few years of CBM development in the Wyoming portion of the Powder River Basin, operators were permitted either to construct dams in ephemeral channels or modify existing on-channel dams and impoundments for temporary storage of CBM produced water. Recognizing the potential interference of these on-channel impoundments with priority water rights of downstream water rights holders, permitting of impoundments by the State Engineer's Office may require a bypass around an impoundment to address downstream water rights. In the Powder River Basin, approximately 2,500 impoundments are on-channel (Fischer, 2005).

An additional, relatively recent requirement being applied to some off-channel impoundments is lining with impermeable materials to minimize the amount of water leaking from impoundments to shallow alluvial groundwater. Presently, about 200 unlined off-channel impoundments in Wyoming may facilitate infiltration or recharge of underlying groundwater (Fischer, 2005). Often, no shallow groundwater is present beneath the impoundments to a depth of several hundred feet so shallow groundwater is thus not recharged or impacted. Specific provisions apply to the location of off-channel impoundments: they may not be sited within 500 feet of a designated water feature (nor less than 500 feet from the outermost floodplain or shallow channel alluvium), as identified on a U.S. Geological Survey 1:24,000 scale topographic map, including perennial and ephemeral streams, dry washes, marshes, and lakes. New guidelines for construction of impoundments, pre-construction groundwater monitoring, and compliance groundwater monitoring once discharge of produced water into the impoundment has commenced have recently been instituted in Wyoming (see Chapter 3).

The initial quality of water in the impoundments reflects the chemistry of the produced water being discharged to the impoundments, which may or may not have been treated prior to disposal depending upon initial water quality and discharge requirements. However, as numerous studies have shown, impoundment water chemistry generally changes over time, with subsequent increases in salinity and trace element concentration (see Chapter 5). As noted in Table 4.2, some of the proposed ancillary benefits of disposal of CBM produced water in surface impoundments include livestock or wildlife watering, or infiltration to shallow alluvial aquifers. Livestock and wildlife watering are described in the next section under "Beneficial Use Options." The committee was unable to find documented evidence of measured alluvial aquifer recharge consequent to introduction of CBM produced water to impoundments.

Land-Applied Disposal Through Water Spreading and Managed Irrigation

During early stages of development of the CBM industry in the Powder River Basin, a technique referred to as "land-applied disposal" was adopted by several of the principal gas and water producers. Land-applied disposal was the term used to describe spreading of large volumes of untreated produced water across agricultural fields using sprinkler irrigation systems, with the expectation of increasing rangeland or cultivated forage production while simultaneously disposing of large volumes of produced water. Studies of this practice revealed that the technique was not sustainable in many locations, due to substantial deterioration in soil structure caused by the effect of applied salts and sodium on some soils of the basin (see Chapter 5). As a result, operators and water resource managers recognized the need for either preventive or intervention soil management actions, including the use of soil amendments (primarily gypsum as a calcium source and sulfur as an acidifying agent), in order for land-applied disposal to remain sustainable. Subsequently, the technique of land-applied disposal was relabeled as "managed irrigation," which combines the simultaneous application of amendments[2] with water spreading.

Irrigation or land spreading of saline-sodic water as a mechanism to use or disperse produced water can be feasible. However, the requirements for management and sustainability of this practice are likely to be unachievable in marginally productive areas, in areas where scientific irrigation water management and monitoring have not previously been used, and in areas where irrigated crop production is marginally economical, except when used as a means of water disposal in comparison to water treatment or other water disposal costs. Under careful management, ancillary benefits of land spreading of CBM produced

[2]Soil "amendments" such as gypsum and elemental sulfur may be added to agricultural soils to liberate sodium. This release of sodium, accompanied by a supply of calcium, enhances improvement in soil structure, and sodium-affected soils can be restored to agricultural productivity. Soil amendments are sometimes called "soil conditioners."

water are rangeland habitat improvement, increased forage production, and shallow alluvial aquifer recharge.

Beneficial Use Options

In the arid and semi-arid landscapes of the study area, water, or lack thereof, is often the single most influential factor in land suitability for multiple uses. Under most circumstances, the addition of water is presumed to result in enhanced landscape quality, whether as a result of increased forage production for livestock and wildlife grazing and habitat, sustained instream flows during dry periods, or sustainability of diverse communities of native plant species. At present, however, little evidence or concerted effort exists to document that CBM produced water has been put to beneficial use for rangeland, wildlife, or stream augmentation. Although the long-term effects of putting CBM produced water to widespread beneficial use in these specific applications are not known, the next sections describe both known (and practiced) beneficial uses as well as those that are not widely applied or documented.

Surface Irrigation

Livestock production is the most economically significant agricultural land use in many locales of the western United States where CBM production has expanded rapidly in the past decade. Most of these areas are characterized by semiarid climates, where evaporative demand far exceeds annual precipitation. Correspondingly, with the exception of stream and river floodplains and mountain valleys, most of the associated landscapes are "rangelands," dominated by sparsely growing native grasses, forbs,[3] shrubs, and drought-tolerant woody plant species. Livestock production is sustained by rangeland and forest grazing, supplemented by winter feeding of grass and alfalfa hay reserves harvested along stream and river corridors during the summer growing season. Where water of sufficient quantity and quality is available, irrigation has been developed to expand livestock forage production as a source of winter feedstocks. In 2007, Montana and Wyoming produced approximately 6 million tons of hay (for livestock feed) with a gross economic value of nearly $630 million.[4]

Correspondingly, irrigation is a mainstay of the agricultural industry tied to livestock production in the western United States. Abundant supplies of water with salt concentrations low enough to meet water quality requirements of irrigated croplands offer the potential to supplement and replace existing water supplies, while doubling or tripling the capacity of arid landscapes to produce feed for livestock. However, neither all water nor all

[3]Forbs are herbaceous flowering plants.

[4]Statistics are sourced from the National Agricultural Statistics Service, available at www.nass.usda.gov/QuickStats/indexbysubject.jsp?Pass_group=Livestock+%26+Animals (accessed January 27, 2010).

landscapes are of suitable quality to support sustained irrigated agriculture. Water quality, soil compatibility requirements, and agricultural plant tolerances to salinity, including irrigation, are provided in Ayers and Westcot (1994).

Although the chemical characteristics of CBM produced water vary significantly from discharge point to discharge point, salinity and sodicity are generally the two principal water quality characteristics of significance and concern with respect to irrigation or land-applied disposal of CBM produced water. Concerns have thus been raised regarding widescale potential beneficial use of CBM produced water for irrigation of agricultural crops.

Currently, more than 8,000 acres of agricultural cropland, primarily grass and alfalfa, are being irrigated by sprinkler irrigation with CBM produced water in the Powder River Basin. This area comprises approximately 6,000 acres in Wyoming and 2,000 acres in Montana. Only 8 percent of the CBM water produced in the Wyoming Powder River Basin was used for managed surface irrigation in 2008 (approximately 9,167 acre-feet or 71 million barrels; Box 4.1). In Wyoming a permit from the Wyoming DEQ is required for surface irrigation if the produced water is obtained directly from the well head. However, if the produced water derives from a permitted surface impoundment, no permit is currently required for the application of produced water to agricultural fields (Wyoming DEQ, 2009). As noted in Table 4.2, ancillary benefits of using CBM produced water for surface irrigation, under careful management, include rangeland habitat restoration, streamflow augmentation, and reduced potential for stream dewatering (see also Chapter 5 for specific effects).

Subsurface Drip Irrigation

A relatively recent development for beneficial use and management of produced water from CBM production in the Powder River Basin is subsurface drip irrigation (SDI), sometimes also called "horizontal injection." This system involves uniformly discharging produced water below ground, near the bottom of the root zone in agricultural fields, through a network of buried pipelines. The water is discharged to serve multiple purposes, including cropland irrigation, enhanced salt leaching from the soil profile, disposal of excess produced water, and shallow alluvial aquifer recharge.

An SDI system is constructed by installing a network of buried tubing that spreads filtered, treated water uniformly, near the bottom of the root zone. The tubing contains precisely spaced emitters that regulate water flow into the soil. Presently, SDI is being used on irrigated fields ranging in size from 20 to 500 acres.

Instead of containment ponds or impoundments, lined surge ponds are built for off-gassing bicarbonate in the produced water. The containment ponds are approximately 2 to 4 acres in area and are about 20 feet deep. The surge pond water level is maintained by the CBM produced water pipeline network. The water is pumped from the surge pond into a small pump house. Degassed produced water is then pretreated according to site-specific chemistry requirements and transported to field valves that release the water to multiple underground tube lines. A 100-acre field may use 3 to 4 million barrels (400 to 500 acre feet) of water in a year.

This style of irrigation is employed as a means of increasing crop yields while preventing salt and sodium accumulation in surface soils with a minimum of surface disturbance or surface infrastructure after the subsurface drip system has been installed (BeneTerra, 2010). This style of irrigation has the potential to apply two to three times more water on a particular site than traditional surface irrigation because water is introduced near the bottom of the root zone. Although SDI can be employed year-round and can be scaled to accommodate changing water volumes from CBM wells, the longer-term, finite lifetime of CBM wells and the associated produced water supply are factors to consider with regard to planning these irrigation areas.

In the Powder River Basin of Wyoming, SDI is regulated under the UIC program, and permits are required from the Wyoming DEQ; in 2008 about 5 percent of the total amount of CBM water produced was used for UIC SDI (Box 4.1). Monitoring of these SDI areas is being conducted by the USGS and a private company specializing in SDI installation and management. The primary focus of the monitoring efforts has been to determine relationships between SDI water discharge and shallow alluvial groundwater quality. Potential primary environmental and ecological benefits include increased crop or forage production. Although shallow alluvial aquifer recharge may also occur as an ancillary benefit, such recharge is not a specific intention of SDI facilities. The facilities are rather designed to ensure that groundwater and surface waters will not be impaired.

Livestock and Wildlife Water Supplies

The capacity of arid and semiarid landscapes to support livestock production is closely associated with the availability, quality, and distribution of livestock-consumable water, although livestock can tolerate a range of contaminants in their drinking water (Ayers and Westcot, 1994). In general, animals can often tolerate elevated levels of salinity if they are allowed the opportunity to gradually acclimate to higher salinity levels and water is available in abundant supply. Water with a TDS level of less than 1,000 mg/L is considered to be suitable as a livestock water source. Water with TDS from 1,000 to 7,000 mg/L can be used as a water source for livestock, although consumption of water having a TDS greater than 5,000 mg/L is often associated with intestinal distress. Produced waters of the Raton, San Juan, Uinta, and Piceance basins typically have TDS concentrations that preclude use of produced waters for livestock watering without treatment or blending with less saline water (see Table 2.2).

Numerous CBM projects in the Powder River Basin have created off-channel impoundments or watering stations to provide untreated CBM produced water as a water source for livestock. ALL Consulting (2003) describes an example from the 7 Ranch near Gillette, Wyoming, where livestock are watered from small reservoirs and old heavy-vehicle tires are used as watering tanks. Ancillary benefits of the use of CBM produced water for livestock include enhanced forage production and use by wildlife and waterfowl.

Instream Flow and Wetland Augmentation

A possible ancillary benefit of discharging CBM produced water to streams is enhancement of instream flow. As discussed in Chapter 3, instream flow is considered a beneficial use in most western states, and release of CBM produced water to streams, if the quality meets surface water and aquatic life standards, can enhance aquatic environments and increase riparian vegetation, providing habitat for birds and other wildlife. An additional ancillary benefit of instream flow augmentation is increased flow to downstream water users. Discharge of CBM waters to wetlands may also enhance these environments and provide ancillary benefits to waterfowl and wildlife if the water quality meets surface water and aquatic life standards. At present, the only areas where this type of CBM produced water benefit might be realized to any degree are the Powder River Basin and the Colorado portion of the Raton Basin. The committee found no referenced evidence that produced water is being managed specifically to achieve these benefits at this time.

Industrial and Municipal Use Opportunities for Produced Water

Although constrained by available infrastructure, transportation costs, and costs of treating water, CBM produced water is also a candidate for beneficial or supplemental use in a number of industrial and municipal applications (see Table 4.3). Such industries and municipalities would likely need to be located near methane- and water-producing areas, to assure minimal costs for transporting water. Currently, no CBM produced water in the Powder River Basin of Wyoming is used for municipal or industrial activities other than for dust control at nearby coal mines and on rural graveled roads. The committee is aware of only a few cases in which produced water from any oil and gas activity—not CBM produced water—was used for potable supplies (Stewart, 2006; Stewart and Takichi, 2007; see Box 4.2). As mentioned previously, a small amount of CBM produced water in Montana is used for industrial dust control (Box 4.1).

CBM WATER AS A BENEFICIAL COMMODITY?

Putting CBM produced water to beneficial use requires an understanding of both quantity and quality issues. Some CBM produced water, for example from the Powder River Basin and some parts of the Colorado portion of the Raton Basin, is suitable for livestock

TABLE 4.3 Summary of Industry and Municipal Beneficial Use Options for CBM Produced Water in the Western United States.

Sector	Beneficial Uses	Treatment That May Be Necessary[a]
Coal mining/mineral extraction	Dust control, fire control and suppression, materials transport, mineral processing support, restoration/ reclamation	None
Livestock production/feedlots	Livestock watering, cleaning, management of animal wastes	None
Industrial cooling towers: coal- and gas-fired electric generation	Facilities cooling	TDS, carbonate, bicarbonate reduction, pH adjustment
Vehicle and equipment cleaning and washing facilities	Vehicle washing (weed control)	None
Oil and gas exploration and extraction	Facilitating drilling, waterflooding, secondary recovery, equipment cleaning	None
Fisheries-aquaculture	Fish production/rearing areas	Managed TDS and constituents, temperature
Municipalities	Fire control/protection	None
Municipalities	Augmentation of municipal potable water supplies	Treatment to regulated standards

[a]Whether treatment is necessary is dependent upon the intended use and water quality required for the use. Presently, for example, treatment of water designated for reclamation/restoration of mined lands or for livestock is not necessary if the quality of the water meets requirements for the desired purpose. In the case of industrial uses and ancillary uses or benefits of CBM produced water, the use of the water is totally elective and any treatment that is imposed is for the purpose of facilitating the use or functionality of the water, but would not be a regulatory requirement.
NOTE: The table information indicates opportunities for major industry uses but is not a comprehensive presentation of all possible industrial uses for CBM produced water. Lack of accessibility to and sustainability of water supplies for the indicated potential use may limit opportunity for beneficial use.

BOX 4.2
Making "Bad" Produced Water "Good": Achieving Augmentation with Water Produced from Oil and Gas Operations—in Wellington, Colorado

The potential opportunities for use of produced water are numerous, but few of those opportunities have been realized to any level of significance. One case that represents the extreme in making beneficial use of produced water is that of the community of Wellington, Colorado, and its partnership with an environmental consulting firm from Fort Collins, Colorado. Wellington, a community outside Fort Collins, Colorado has experienced rapid expansion in population over the past two decades, but without similarly increasing the availability of desired municipal water supplies. A combination of drought and senior water rights holders' demands for water for irrigation have put the city of Wellington in a situation with slowly depleting storages of water in underground aquifers that the city relies on for municipal water.

The Wellington project is treating water produced from conventional oil wells as a raw water resource to augment shallow water aquifers to ensure adequate water supplies for holders of senior water rights downstream of Wellington. The process is known as aquifer storage and recovery (ASR). A participating oil company engaged with the environmental consulting firm and Wellington to allow the petroleum operator to increase its oil production, resulting in more produced water than they could adequately manage. The environmental consulting firm agreed to take possession of the "newly produced" water, treat the water, and then use the treated water as an augmentation water source to resupply the aquifer from which Wellington was drawing water for municipal use. The augmentation water mixes with water within the shallow alluvium, down gradient of the Wellington municipal water withdrawal, and subsequently satisfies the water rights of downstream senior water rights holders.

One of the unique features of this project, in addition to transforming produced water, which normally would be considered a waste, into "good" water used to satisfy an augmentation requirement imposed on the community of Wellington, is the legal recognition of some produced waters as "new" water, or new water resources for the western United States. In addition, this whole new approach to "produced water" as a beneficial use product and augmentation source of water has tested the premise of the "nontributary" nature of water produced from conventional oil wells, the assignment of ownership of "new" water, and how water resource management and regulatory agencies approach new and novel beneficial use applications of produced water.

SOURCES: See Stewart (2006); Stewart and Takichi (2007); Henderson (2007); Veil et al. (2004); and www.netl.doe.gov/technologies/pwmis/techdesc/injectfut/index.html (accessed March 9, 2010).

watering and wildlife use and consumption directly after it emerges at the well head with no prior treatment. Other produced water may be of suitable quality for establishing and maintaining wetlands. With current technologies, CBM produced water can be treated to attain the quality necessary to support any beneficial use, but at variable costs. At present, however, water coproduced with CBM has been largely neglected for beneficial use, even where concentrations of dissolved solids and other contaminants are within regulatory guidelines for potable agricultural or livestock use, such as described earlier for parts of the

Powder River Basin. With appropriate management, assurances of compatibility between CBM produced water quality, crop sensitivity to salinity, and soil properties, CBM produced water may be used to augment site-specific water supplies for irrigated agriculture in some areas.

State regulatory frameworks for environmental management and mineral and water rights have been the greatest influence on the way in which produced water can and has been used in the western states (see Chapter 3). This influence extends to any market value, whether real or perceived, of produced water used for beneficial purposes. Today, western cities look to enhance their water supplies, sometimes at significant cost. The societal and economic costs that may be incurred by not considering CBM water for beneficial use in an arid part of the United States are not usually discussed with regard to CBM produced water management.

In concept and on paper, putting CBM produced water to beneficial use would seem to be a desirable and relatively easy objective to achieve. In reality, management or discharge of CBM produced water for the specific purpose of achieving beneficial use is potentially economically burdensome, complex, and challenging. For example, in the case of waterfowl habitat enhancement, either constructing or intentionally augmenting existing ponds and wetland areas by discharging CBM produced water on the landscape typically requires an NPDES permit. The process of preparing and submitting applications for such a permit is both economically burdensome and labor intensive for the applicant. Consideration must be given to the quality of the discharged water, the potential for flooding, seepage to downgradient ephemeral channels or shallow alluvium, alteration in the ecological community resulting from changes in hydrology of the wetland, short- and long-term impacts of discharge on the chemistry of the impounded water, and the longevity or tenure of available supplies of produced water to support waterfowl habitat. Consideration also needs to be given to the potential consequence of discontinuation of the augmentation as CBM production diminishes.

Another example might be that of instream flow augmentation and corresponding supplementation of downstream irrigation water sources. Discharge requires an NPDES permit, which might require treatment of discharged water to assure protection of aquatic species. The rigor or level of treatment of water to achieve aquatic species protection may far exceed the treatment level that would be required to support sustainable irrigation—yet both beneficial uses are intended with the same CBM produced water discharge, creating added challenges with regard to permitting, compliance, and economics of managing the CBM produced water.

Discharging produced water to an existing stream for the purpose of fisheries enhancement could result in blended water that is not of an acceptable quality for downstream irrigation uses. The beneficial use opportunity is dictated by the quality in stream. Acceptable quality for one beneficial use may preclude use of the water for other uses, or may even impair the water quality with respect to other uses. Each beneficial use has a potentially different acceptable quality—and not necessarily the quality of CBM produced water.

Each beneficial use also aligns with a set of criteria, and acceptable or appropriate criteria for one beneficial use may be in direct conflict with the criteria for another beneficial use. For instance, in the case of discharging CBM produced water for wildlife habitat enhancement, research has shown that the chemistry of impounded water changes over time and, consequently, that such water may become deleterious to wildlife health over time. In the case of discharge to a stream to supplement downstream irrigation, existing stream channels reflect a geomorphological evolution, which may be substantially altered by flow augmentation. Additional complications and hindrances are introduced when consideration

BOX 4.3
First-Order Estimation of the Market Value of CBM Produced Water Since Production Began in Wyoming

Water for domestic use in Denver (as an example) costs on the order of $4,000 per acre-foot[a] for a water right. Lease rates for water with at least a 10-year guaranteed supply sold to urban Denver buyers averaged $5,000 per acre-foot (in 2009 dollars).[b] As shown in the figure below, the potential value of CBM produced water today, if shipped to Denver, would be on the order of hundreds of millions of dollars per year at current market value. The cost of a 10-inch pipeline needed to move water from Wyoming to Colorado would be about $500,000 per mile. For roughly 400 miles of pipeline (the distance from the CBM producing areas of the Wyoming Powder River Basin to Denver), the approximate cost would be on the order of $200 million. At a supply of 75,000 acre-feet per year, the cost of the pipeline and other related business expenses would be covered inside of one year. These calculations do not include water treatment costs that would have to be borne if the water did not emerge from the well head in the Powder River Basin (or another basin) within regulatory standards for potable water. The energy cost of pumping water at 1,000 gallons per minute (with a lift of about 1,000 feet from the Powder River Basin to Denver would be about $20 per acre-foot assuming a lift cost of 1 cent per kilowatt-hour and 90 percent pump and motor efficiencies).[c] Even assuming much higher power rates and the construction of pump stations, the power costs appear relatively small.

While this type of calculation is intentionally simplistic, it illustrates the value or potential value of a resource, water, which is otherwise largely disposed of in a part of the country that historically suffers from water stress. The complications of this issue are significant and include effects of CBM produced water on groundwater and surface water resources (as discussed in Chapter 5); costs at various parts of the beneficial use chain, including production of the water, water treatment, and any storage or transportation of the water (Chapter 6); the consistency or sustainability of the produced water resource supply (Chapter 2); and the regulatory constraints both within and between states (Chapter 3). Of relevance to the discussion is also the fact that CBM produced water has never been considered available for a water right since CBM produced water is not available on a permanent basis. Therefore, CBM produced water at present has no legal ownership that can be assigned or transferred to a vendor which is the current basis for the situation that an operator can treat CBM produced water, but cannot sell it.

is given to liability, water rights regulations, and sustainability of supply issues. These circumstances, in addition to the general decrease in volume of CBM produced water over the lifetime of a well, make CBM produced water an uncertainty and only a temporary source of water for beneficial use. This uncertainty contributes to the difficulty of addressing opportunities for beneficial use.

For the purposes of adding some quantitative value to this discussion, the committee attempted to generate a simple answer to the question "What might be the economics of using high-quality CBM produced water as a commodity?" The resulting Fermi calculation illustrates the potential value of the total amount of CBM water produced per year now in the Powder River Basin in Wyoming (see Box 4.3). Fermi-type calculations, even

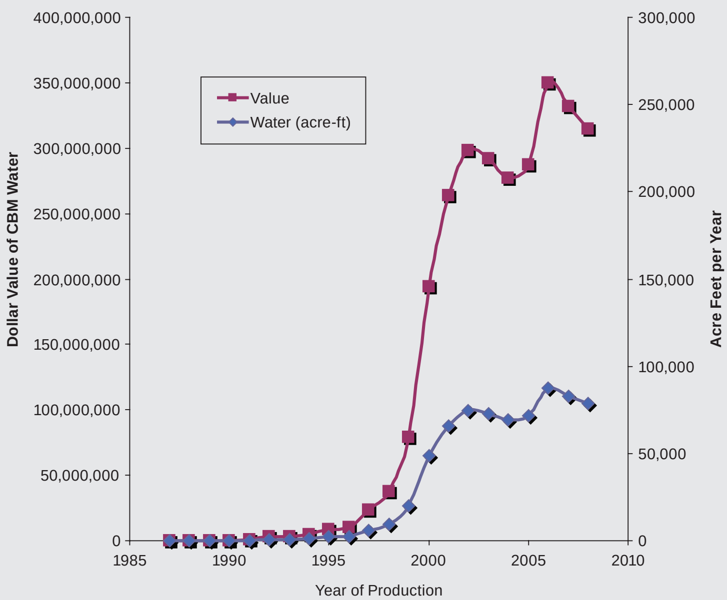

FIGURE The blue curve shows to the total acre-feet of CBM produced water from the Wyoming portion of the Powder River Basin from the mid-1980s through 2009 (corresponding to the vertical scale on the right-hand side; see Chapter 2). The red curve, corresponding to the vertical scale on the left-hand side of the diagram, shows the calculated potential market value of CBM produced water, if shipped to Denver, using the conservative value of $4,000 per acre-foot for domestic use in Denver for each year. In other words, if all of the produced water from the Wyoming portion of the Powder River Basin in 2009 (about 78,000 acre-feet) was shipped and sold to Denver, the market value of the water would be 78,000 acre-feet x $4,000 per acre-foot = $312 million. This "market value" for the water is greater than the estimated cost of building the water pipeline.

[a]See www.waterexchange.com/Deepwater.aspx (accessed March 10, 2010).
[b]See www.bren.ucsb.edu/news/water_transfers.htm (accessed April 27, 2010).
[c]See www.engineeringtoolbox.com/water-pumping-costs-d_1527.html (accessed April 27, 2010).

at order-of-magnitude or factor ranges of accuracy, are used to frame issues so they can be easily conceptualized for consideration by different parties in more detail (Harte, 1988; Weinstein and Adam, 2008). The committee emphasizes that Box 4.3 does not provide a comprehensive cost-benefit analysis of potential uses of CBM produced water, but is intended as a tool to facilitate communication about considering options for potential use of CBM produced water as opposed to simply disposing of the water.

CHAPTER SUMMARY

CBM produced water is currently being managed either as a waste product or as a water resource that can be put to beneficial use, although the management as a waste product far exceeds use of CBM produced water as a beneficial natural resource. Irrespective of which avenue is taken, production, handling, management, and/or disposal of produced water all contribute to the cost of production of CBM (discussed further in Chapter 6). Few instances are reported in the industry or scientific literature wherein CBM produced water constitutes an income stream for energy producers. In concept and on paper, putting CBM produced water to beneficial use would seem to be a desirable and relatively easy objective to achieve. In reality, management or discharge of CBM produced water for the specific purpose of achieving beneficial use is potentially economically burdensome, complex, and challenging.

Produced water is a necessary byproduct of CBM extraction, although the amount of water produced per unit of natural gas recovered and the quality of water produced vary significantly among CBM producing basins. Additionally, the amount of water produced per CBM well typically decreases as the life of the well is extended (see Chapter 2). These circumstances make CBM produced water an uncertainty and only a temporary source of water for beneficial use. Thus, although CBM produced water does have a value, and even though its availability is transient, this uncertainty in availability contributes to the difficulty of addressing opportunities for beneficial use.

Less than 5 percent of all CBM produced water in the six western states considered here is directly or intentionally beneficially used for irrigation of agricultural lands. With the exception of livestock watering, essentially all other beneficial uses of this water are ancillary or consequential to disposal through discharge—e.g., streamflow augmentation, wildlife and aquatic habitat enhancement, aquifer recharge, and wildlife watering.

Nearly 85 percent of all CBM produced water in the Powder River Basin (Wyoming and Montana combined) is disposed of either by storage in constructed impoundments or direct, permitted discharge to ephemeral drainages and perennial streams. This approach to produced water management is driven by large volumes and relatively low salinities of produced water (see Chapter 2) and the regulatory ease and environmental suitability of discharge or storage.

This management contrasts with the San Juan, Uinta, New Mexico portion of the Raton, and the Piceance Basins, where essentially all water produced as a consequence of CBM production is disposed of through reinjection to geological formations deep below drinking water supplies or CBM aquifers. This approach to produced water management is driven by small volumes and high salinities of produced water, regulatory ease and environmental suitability of deep reinjection, and the high costs of treatment to achieve water quality conditions compatible with beneficial use options.

The potential economic, ecological, and environment value or benefits of CBM produced water, either in its present state or following necessary treatment, have not been fully evaluated. Intentionally simplistic calculations of the potential economic value of CBM produced water from the Powder River Basin, based on the past 15 years of reported water production, suggest commercial significance of this produced water for municipal purposes. While the specific dollar value of the water may change with different input parameters, the intrinsic value of the CBM produced water resides in the fact that it can be used and is irreplaceable.

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CHAPTER FIVE

Environmental Effects of Coalbed Methane Development and Produced Water Management

An element of the committee's charge includes identifying documented positive and negative effects of coalbed methane (CBM) produced water on the quality and quantity of surface water and groundwater resources, soil resources, and ecological communities. This chapter is weighted toward discussion about the Powder River Basin because large volumes of CBM produced water are discharged to surface waters or impoundments or are being put to beneficial use there, relative to other western CBM basins. Correspondingly, most of the scientific literature on the environmental effects of CBM produced water and most of the controversy that has precipitated litigation or media attention about CBM produced water management has originated from research conducted in this basin. With deep re-injection the primary method of CBM produced water management in the other western CBM basins, fewer perceived or documented effects on the surface environment or shallow groundwater have contributed to less litigation, less media attention, and fewer studies of environmental effects being completed in those basins. Data that characterize the quality of waters in the geologic formations used for reinjection are not readily available, but can be inferred from borehole logs.

Reports from private citizens on the effects of CBM produced water on the environment were also instrumental in focusing some committee attention to examining potential research or information gaps associated with CBM produced water management. This chapter contains a review of registered citizen complaint information from several official state websites and identifies several cases in which the complaints were brought to court.

GROUNDWATER

The primary substantiated effects of CBM produced water on groundwater resources include (1) drawdown of groundwater levels in coalbeds as a result of pumping water from coalbeds during CBM extraction and (2) changes in groundwater quality associated with

CBM produced water in surface impoundments. These effects and their potential causes are addressed below. Although adverse effects from hydraulic fracturing have not been documented in CBM fields, the issue is of concern to the public. A brief discussion of hydraulic fracturing is included at the end of this section.

Effects of Groundwater Withdrawal on Aquifers

Research demonstrates that a principal effect of CBM withdrawals on groundwater is reduction of water volume and hydrostatic head within coalbeds from which methane is being extracted. Typically, the CBM well is pumped to reduce the hydrostatic pressure in the coalbed to a pressure approximately equal to atmospheric. However, water is still retained within the coal and generally the head level of water in the coalbed is maintained relatively close to the uppermost physical surface of the coalbed. Any effects of water withdrawal from methane-bearing coalbeds on water levels in other aquifers are a function of the depth of the target coalbeds and the degree of hydraulic connection between CBM targets and the other local or regional aquifers (see Chapter 2 for discussion of hydraulic connectivity).

Pumping water during CBM extraction in basins with deep methane-bearing coals, such as the San Juan, Raton, Uinta, and Piceance basins, is unlikely to cause lowering of the water table of shallow alluvial aquifers because of lack of hydraulic connectivity between the deep coals and shallow aquifers coupled with the great vertical separation between the coalbeds and the shallow groundwater systems (upward of thousands of feet; see also Chapter 2). Typically, methane-bearing coalbeds in these basins are bounded above and below by either aquitards or aquicludes (see Chapter 2) that are responsible for both the positive hydrostatic pressure within the coalbeds and the lack of hydraulic connectivity or communication between the coalbeds and overlying and underlying aquifers. An exception to this circumstance is that reported by Riese et al. (2005) for the San Juan Basin, in which the authors documented movement of water from below the methane-bearing coalbeds upward and into the coalbeds (see Chapter 2).

In contrast, depths to methane-bearing coalbeds in the Powder River Basin are relatively shallow and less consolidated than those of the other western CBM basins (see Chapter 2). Consequently, the coalbeds generally consist of porous and permeable formations capable of releasing large amounts of water during methane production (see Table 2.1). Some of the coalbeds or fringes of coalbeds in the Powder River Basin are also sufficiently close to the land surface that they serve as sources of domestic, residential, wildlife, and livestock water supply (Frost et al., 2010; Wheaton et al., 2005; Campbell et al., 2008). These supplies often surface as flowing springs and wells. In some instances wells are drilled into the coalbeds and the water is used for stock watering or domestic supplies. However, direct physical connections between water-bearing coalbed aquifers from which CBM is being extracted and other alluvial groundwater that supplies water wells and springs in the basin are not widely established; geochemical data suggest that coal aquifers and other alluvial groundwater aquifers do not interact to any great degree in studied parts of the Powder River Basin (see discussion in e.g., Frost et al., 2010; Bartos and Ogle, 2002; see also Chapter 2). Anecdotally, CBM production has been linked to some losses of drinking water or dry wells where the water wells were close to the CBM development and/or were completed in the coals which serve as a primary aquifer.

In addition to geochemical information that can help determine the degree of connectivity between CBM coalbeds and other groundwater aquifers, groundwater monitoring networks are being used to measure the degree to which CBM production may affect water levels in shallow aquifers. The Montana Bureau of Mines and Geology (MBMG) maintains and samples a regional network of groundwater monitoring wells that includes wells installed in the late 1970s and early 1980s to monitor the effects of coal mine dewatering, a separate activity from CBM operations, and more recent wells installed specifically to monitor CBM production. The MBMG receives funding from the Bureau of Land Management (BLM) in support of this monitoring program. In Wyoming, in response to concerns about potential effects to groundwater from CBM development in the Powder River Basin, BLM established a regional groundwater monitoring program that is outlined as part of the Wyodak CBM Final Environmental Impact Statement (BLM, 1999). The program was designed to collect information regarding hydraulic connectivity between producing coals and adjacent sandstone units and to measure the extent of groundwater drawdown in the CBM-producing coal zone on federally owned lands. Results from both the Montana and Wyoming groundwater well monitoring programs are briefly summarized below.

Montana

Many of the monitoring wells are completed in the Dietz (associated with the Anderson coalbeds) and Canyon coalbeds in the Powder River Basin (Wheaton and Metesh, 2002; see also Figure 2.4b). The monitoring network has been sampled for seven consecutive years (2003–2009), in addition to sporadic monitoring for nearly three decades before CBM development was initiated in the area, and the data are available in annual reports through the 2008 sampling event.[1]

Data from this network indicate that static water levels in the Dietz coalbeds, from which CBM is being extracted, have been lowered by as much as 150 feet. Static water levels in the Canyon coal, also a coalbed from which CBM is being extracted, have been lowered as much as 600 feet in limited areas (Meredith et al., 2008). CBM-related drawdown of 20 feet of the static water level in the Canyon and Dietz coalbeds currently extends to

[1]See, for example, Wheaton and Donato (2004), Wheaton et al. (2005, 2006, 2007, 2008), Meredith et al. (2008), and Wheaton and Meredith (2009).

roughly 1 to 1.5 miles outside the CBM fields. Although little change in the water levels of the monitored coalbeds in Montana has been observed since 2004, the areal extent of water drawdown in the coalbeds is predicted to increase in the future as CBM production increases (see also Chapter 1). Meredith et al. (2008) predicted the 20-foot drawdown contour to expand to 4 miles beyond the edges of the large production fields. Results from these studies apply specifically to drawdown in the Dietz and Canyon coalbeds, which are uniquely identifiable and distinguishable coal- and methane-bearing aquifers; however, as noted above and in Chapter 2, these coalbeds, while regionally pervasive, are not necessarily the same as shallow alluvial coalbed aquifers that may supply substantial domestic and livestock water or contribute to significant base flow of perennial water resources in this area.

Groundwater models and monitoring results have been interpreted to indicate that water levels in the Anderson-Dietz and Canyon coals will take decades to return to original levels (Wheaton and Meredith, 2009). The extent of water level drawdown in the coalbeds and the time to recovery depend on (1) proximity to CBM production, (2) site-specific aquifer characteristics, (3) proximity to recharge areas, and, potentially also, (4) connection or access in the coalbeds to water from deeper horizons (Meredith et al., 2008). On the edge of the basin, near recharge areas, 75 percent recovery occurred within five years of the monitoring period when pumping was discontinued in the Anderson coal formation. In the center of the area monitored, where pumping was most aggressive, groundwater levels in the Anderson coal have recovered 65 percent in 10 years (Wheaton and Meredith, 2009). An example of groundwater drawdown and recovery in several wells in the Anderson-Dietz coal aquifer in Montana is shown in Figure 5.1. Sufficient data have not been collected at this point to either (1) characterize the contributing sources to recharge or (2) determine through geochemistry comparisons whether the recharge water is the same as or uniquely different from water currently within the coalbeds. In the latter case, recharge could be attributed to redistribution of water due to pressure (or head) gradients resulting from several years of pumping.

Wyoming

In the Wyoming portion of the Powder River Basin, the Wyoming State Geological Survey, in collaboration with BLM, analyzed data from 111 wells in the BLM deep-well monitoring network, collected from 1993 to 2006 (Clarey, 2009). The data indicate that drawdown occurs within the coalbeds or coal aquifers ("confined coals") and that the magnitude of drawdown is greater nearer to monitoring wells located in areas of CBM development than in areas peripheral to development, consistent with that reported by Meredith et al. (2008). The measured impacts include a maximum groundwater-level drawdown of up to 625 feet within the coals in Fort Union coal monitoring wells and maximum groundwater-level drawdowns of more than 260 feet in the overlying Wasatch sandstone.

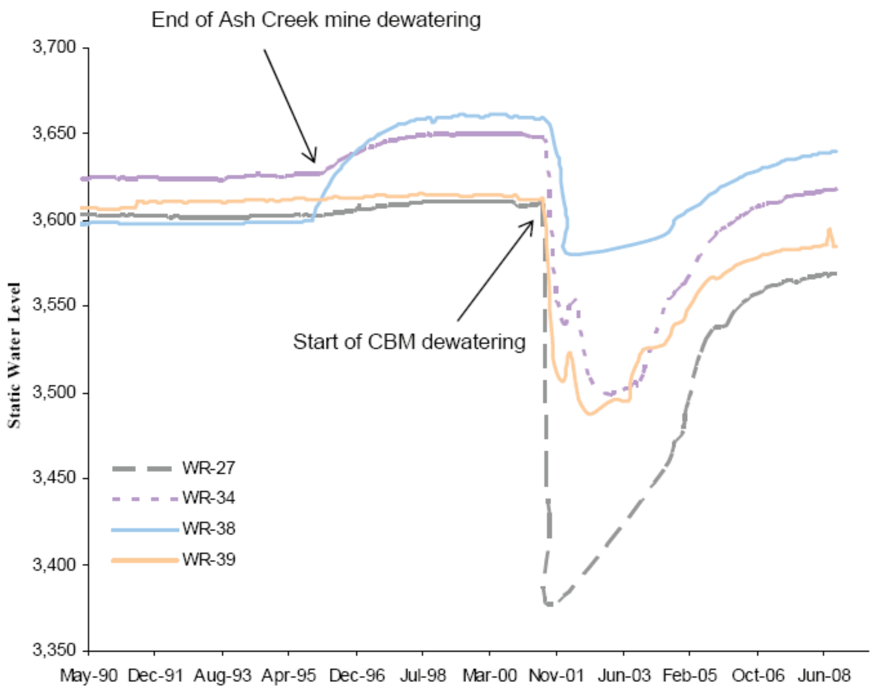

FIGURE 5.1 Measured groundwater elevations in Anderson-Dietz coal seams during and after coal mining dewatering and then following the initiation of CBM-related dewatering. The larger drawdown (80 to 233 feet, starting in 2001) is related to CBM production, and recoveries of 73 to 87 percent over a seven-year period are related to a gradual decrease in CBM production. Full recovery is predicted to take 20 to 30 years. These wells are located in the CX CBM field in the southwestern corner of the Montana portion of the Powder River Basin near the Wyoming border. The original drawdown (pre-1995) in Figure 5.1 was from coal mine dewatering, and water levels largely recovered before CBM production began. SOURCE: Meredith et al. (2008).

Since 1997, hydrological impacts in the Powder River Basin from CBM development have been regionally confined to some of the Tongue River Member coals of the Fort Union Formation and some of the sandstone beds in the overlying Wasatch Formation. The latter sandstones are deeper beds that are in physical contact with the coalbeds. Importantly, these drawdowns are being measured in coals that are the same as the coals being pumped for methane extraction.

Recent modeling studies have shown that CBM impacts to groundwater levels in the upper coal member of the Fort Union Formation are slightly less than the drawdowns modeled and predicted for the year 2006 (AHA and GEC, 2002; Clarey, 2009). The observed drawdowns in the Wasatch sandstone wells were also compared with modeled (predicted) drawdowns (AHA and GEC, 2002). The different sandstone zones within the Wasatch did not show drawdown of Wasatch water levels except for a few limited areas, suggesting limited connectivity of the units. Thus, although pumping of water in Wyoming has been much more aggressive and local to the CBM wells compared to Montana, the conclusions of this analysis in Wyoming are consistent with those reported by Wheaton and Meredith (2009) and in various MBMG reports (see references above).

Importance of Fossil Water

Determining the extent to which CBM produced water is actually fossil water (see Chapter 2) is also important to analyzing the effects on groundwater drawdown. Multiple lines of evidence suggest that CBM produced water in the San Juan Basin and potentially also in the Raton Basin is fossil water with an age of thousands to tens of millions of years. Prior to extraction, the water rested underground in aquifers in these basins over geological timescales, without interacting with or being affected by surface events such as rainfall. Recharge of the San Juan and Raton coalbed aquifers is low because of hydrogeological compartmentalization and the fact that evaporation usually exceeds precipitation in the dry western climate. Data from the Powder River Basin suggest that some of the CBM aquifer water there is also likely at least thousands of years old in aquifers with limited connectivity (see Chapter 2).

Long-term implications of mining fossil water have not been studied or included as part of the discussion of management approaches for CBM produced water. Similarly, basin-wide and comprehensive analyses of the degree of hydraulic connectivity between CBM aquifers and other groundwater aquifers are needed to understand the degree to which CBM waters may be considered "fossil." Such studies have not been thoroughly completed for any basin except the San Juan.

Hydraulic Fracturing

In CBM operations where hydraulic fracturing is regularly used, expressions of concern by the public prompted a study by the U.S. Environmental Protection Agency (EPA) to assess the potential for contamination of underground sources of drinking water (USDWs) as a result of the practice (see also Box 2.1). The study (EPA, 2004) found that, while fracturing fluids contain various chemicals, the identities of which are not generally a reporting requirement for operators, no conclusive evidence of drinking water contamination by hydraulic fracturing fluid injection was found to be associated with CBM wells. Lack of comprehensive datasets and studies, and continued development of domestic oil and gas fields since the release of that report, have continued to focus attention on hydraulic fracturing. The EPA has announced it is conducting a broader analysis of the potential effects on water quality and public health from hydraulic fracturing throughout the entire oil and gas industry (EPA, 2010).

CBM Impoundments and Produced Water Quality

Surface impoundments hold produced water until it evaporates or infiltrates into the subsurface, or they store the water for future beneficial uses (see Chapter 4). In 2008, 64 percent of the CBM produced water in the Wyoming portion of the Powder River Basin was managed in surface impoundments (see Box 4.1). Surface impoundments are not used extensively in the other western CBM basins or in the Montana portion of the Powder River Basin (see Table 4.1 and Chapter 3), although some impoundments (lined and unlined) are used in the Raton Basin in Colorado. Impoundments strictly for storage or disposal (evaporation or infiltration) are no longer permissible in Montana. In the Raton Basin the Colorado Oil and Gas Conservation Commission (COGCC) has indicated some issues related to leaks or seepage from the impoundments either to the surface water or groundwater, but the committee was not able to identify specific data on the extent of any effects of seepage from the impoundments (Ash and Gintautas, 2009). Thus, the remaining discussion focuses specifically on impoundments in the Wyoming portion of the Powder River Basin.

As of 2005, about 2,500 of the approximately 3,000 CBM impoundments in the Powder River Basin were “on-channel” impoundments sited within a water feature (including perennial and ephemeral streams and rivers, dry washes, marshes, and lakes) or within the floodplain or alluvium of a water feature. Roughly 200 impoundments were “off-channel” and unlined, with the intent to recharge underlying groundwater. The remaining off-channel impoundments are lined to reduce, minimize, or prevent leakage and infiltration into underlying soils. According to Wyoming state policy, off-channel impoundments may not be sited within 500 feet of a designated water feature (and must be located at least 500 feet from the outermost floodplain or alluvium; Fischer, 2005a).

In Wyoming, impoundments were initially permitted for the purpose of storage of produced water, although the intent was to facilitate disposal by evaporation, enhanced by atomization, infiltration, or for storage for land spreading or irrigation. Under Wyoming DEQ permitting provisions, a limited number of impoundments were permitted for the purpose of infiltration. Wyoming DEQ presently permits some off-channel impoundments for the purpose of infiltration, but not necessarily with the intent of recharging underlying groundwater. Changes to the guidelines for construction and monitoring of unlined impoundments in Wyoming are outlined in Chapter 3.

Potential groundwater effects from off-channel CBM produced water impoundments relate to the leaching of salts, metals, or metalloids that occur naturally in soils in or under the impoundments and that may be dissolved and mobilized by CBM produced water infiltrating beneath the impoundments (McBeth et al., 2003; Jackson and Reddy, 2007;

Healy et al., 2008). The measured chemical elements of interest include sulfate, selenium, arsenic, manganese, barium, and total dissolved solids (TDS). Geochemical processes involving these constituents can also affect infiltration rates of water into soil over time. Healy et al. (2008) have indicated that high TDS and nitrate and chloride concentrations exist under some CBM water impoundments in the Powder River Basin. The researchers concluded that large amounts of chloride (12,300 kg) and nitrate (13,500 kg) were being leached from soil materials below impoundments into perched groundwater resulting from water infiltrating from the impoundments. Several additional studies in the Powder River Basin of different impoundments (including both on- and off-channel impoundments) and associated groundwater effects are described below to illustrate the various scales at which groundwater data related to impoundments may be analyzed and the effects of the results on management and monitoring requirements.

A preliminary study in 2005 by the Water Quality Division of the Wyoming DEQ on the potential effects on groundwater of CBM impoundments indicated high concentrations of TDS, selenium, and sulfate in groundwater beneath four on-channel impoundment facilities (Fischer, 2005a,b). These concentrations had increased as a result of the infiltration of CBM produced water below the impoundment and subsequent dissolution of minerals and other compounds in the underlying soils. The impact on groundwater quality beneath the impoundments caused the Class of Use of the groundwater to be changed from Class III[2] (livestock use; 3,000 mg/L TDS) to Class IV (industrial use) because of TDS, selenium, and sulfate in excess of Class III standards (Fischer, 2005a,b). As a consequence of these results, the Wyoming DEQ implemented new compliance monitoring guidelines for new CBM impoundments in the state. Continued studies were recommended to determine the effects on groundwater over the entire basin. As mentioned previously, the new guidelines which were developed on the basis of the 2005 study have been updated again and were issued by Wyoming DEQ in April 2010 (see Chapter 3).

As part of its continuing investigation of the extent of groundwater and surface water impacts from impoundments (on- and off-channel) and the length of time these impacts may persist following closure, the Wyoming DEQ Water Quality Division recently completed a comprehensive review of five years of groundwater monitoring data associated with CBM produced water impoundments (on- and off-channel) and their effects on shallow groundwater in the Powder River Basin. Between August 2004 and May 2010, the Wyoming DEQ reviewed data for more than 2,000 CBM produced water impoundments

[2]Class III groundwater in Wyoming is water that is suitable for livestock. The majority of CBM produced water in the Powder River Basin of Wyoming is designated as Class III. Infiltration impoundments in Wyoming are not allowed to be sited over Class I or Class II groundwater.

(Fischer, 2009a,b; see also ALL Consulting, 2008)[3,4] which were drilled to investigate the presence or absence of groundwater. Approximately half of the sites lack groundwater resources to the required depth of investigation, which is either 150 feet or 200 feet below ground surface depending on the size of the impoundment. Those sites that encountered groundwater were sampled and the reports were submitted to DEQ (approximately 900 reports). The Wyoming DEQ has issued permits and associated compliance monitoring programs for approximately 296 impoundments. Many of the impoundments have either never been constructed, have not received discharge, or will not be used. The Wyoming DEQ has issued groundwater monitoring exemptions for approximately 1,485 impoundments because either groundwater was not encountered during the drilling program, or groundwater was Class IV (industrial) quality.

Relative to the 296 impoundments for which permits and associated compliance monitoring programs have been issued, permit-holders for 144 impoundments with 170 associated monitoring wells submitted monitoring reports as of May 2010. The monitoring wells are part of the state's impoundment performance compliance monitoring process and are currently sampled on a scheduled basis (e.g., quarterly, semi-annually, or annually) as required in the monitoring well permit to construct. The impoundments overlie Class III (livestock) quality groundwater and the monitoring reports documented exceedance of groundwater standards beneath 17 impoundments since 2004. The primary constituents identified in groundwater were TDS, sulfate, and/or selenium, largely related to dissolution of soil-associated selenium and pre-existing gypsum (calcium sulfate) salts above the water table. In addition, some impoundments exceeded surface water standards for iron and barium. The state also found about 50 leaking reservoirs that required corrective action (e.g., pump-back systems or cessation of discharge).

In an assessment of the 170 monitoring wells associated with 144 impoundments,[5] specific changes in groundwater level and chemistry of groundwater sampled from the wells were based on identification of four qualitative trends in water geochemistry: (1) stable (no upward or downward trend during the measurement period), (2) upward (increasing salinity and sulfate concentrations), (3) flushed (increasing concentrations followed by decreasing concentrations), or (4) improved (decreasing concentrations of salinity and sulfate). In the majority of instances (72 percent), the trend analyses indicated that CBM water from impoundments resulted in no apparent water quality trend (stable trend) as a result of interaction with the underlying soils. Eighteen percent showed increasing salinity

[3]The study by ALL Consulting was supported by the National Energy Technology Laboratory and was performed in cooperation with the Wyoming DEQ, the Montana Board of Oil and Gas Conservation (MBOGC), the U.S. Geological Survey, and the U.S. Department of Energy. MBOGC provided some funding for the groundwater analysis portion of the study.

[4]Updated figures regarding the ongoing study were provided in June 2010 by D. Fischer (pers. comm.)

[5]C. Steinhorst, Wyoming DEQ Water Quality Bureau, personal communication, Nov. 30, 2009 and August 23, 2010.

and sulfate concentrations at some point in their history (flushed or upward trend), and 6 percent showed improved groundwater quality (see Figure 5.2). Eight of the wells did not clearly fit into any category. Of the 170 wells, 12 exceeded Class III standards (changed from Class III to IV): seven of the monitored wells exceeded standards for sulfate or TDS and five exceeded standards for selenium only. Confined artesian aquifers[6] generally had greater depths to groundwater and lower percentages of wells exhibiting a decrease in water quality. In analysis of some of the same data, the ALL Consulting (2008) study concluded that impacts of CBM produced water impoundments on shallow groundwater were site specific and influenced in large part by the shallow subsurface geology of the area (on-channel versus off-channel). Data gaps identified by the 2008 study included lack of knowledge of the volumes of water discharged into impoundments; absence of analysis of groundwater and CBM produced water for major cations and anions such as calcium, magnesium, sodium, sulfate, chloride, and bicarbonate; and need for evaluation of impoundment inflows to deeper groundwater in order to continue to monitor the effects of CBM produced water infiltration.

Summary of Groundwater Studies

Primary considerations with respect to CBM produced water and effects on groundwater are (1) drawdown of groundwater levels in coalbeds as a result of pumping water during CBM extraction and (2) changes in groundwater quality beneath surface impoundments associated with leakage of stored CBM produced water. Groundwater drawdown in any shallow groundwater aquifer as a result of water and methane extraction from CBM operations is a function of the depth to the target coalbeds and the degree of hydraulic connection between CBM targets and other local or regional aquifers. Due to the great distance between the deep coalbeds and shallow groundwater aquifers and to aquifer compartmentalization, pumping water during CBM extraction in basins with deep methane-bearing coals (e.g., the San Juan and Raton basins) is unlikely to cause lowering of the water table of shallow alluvial aquifers.

Groundwater monitoring networks established for coalbeds in the Powder River Basin in Montana and Wyoming have measured the degree to which CBM production has affected water levels in coalbed aquifers, either in proximity to areas of CBM development or near the fringes of the coalbed outcrops. Measured drawdowns ranged between 20 and 625 feet below prepumping levels. These coalbed aquifers are not necessarily the same as shallow alluvial aquifers used frequently as the principal source of water in the area. On the edge of

[6]An artesian aquifer is a confined aquifer (bounded by impermeable geological strata) that contains groundwater that can flow upward through a well (an "artesian well") without pumping.

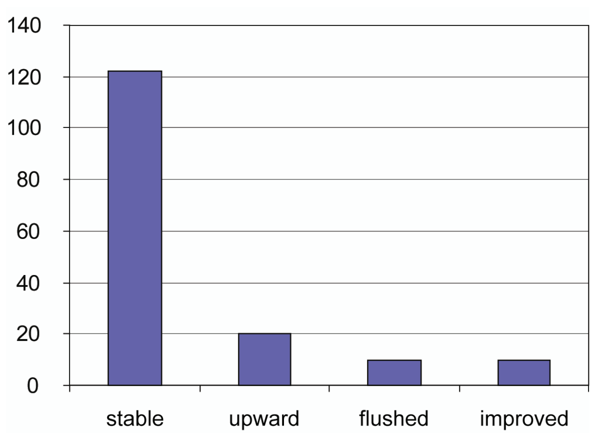

FIGURE 5.2 Graphical distribution of the classification of groundwater data from 162 compliance monitoring wells associated with 144 CBM produced water impoundments. The data showed stable, upward, flushed, or improved geochemical trends in shallow groundwater beneath impoundments. "Improved" indicates reductions in TDS and sulfate concentrations in groundwater over time. Importantly, qualitative classifications based on trend analyses do not imply magnitude or cause of changes to groundwater quality. Another eight wells did not fit clearly into any of the four categories. SOURCE: Adapted from C. Steinhorst, Wyoming DEQ Water Quality Bureau (WQB), personal communication, Dec. 22, 2009 and August 23, 2010.

the basin in Montana, near recharge areas, 75 percent recovery of the water levels in one of these coalbed aquifers occurred within five years when pumping was discontinued. In the center of the area monitored, where pumping was most aggressive, groundwater levels in the affected coalbed for which data were available have recovered 87 percent in 10 years.

Observed drawdowns were less than those predicted in modeling. Although model results predict that recovery to original water levels in the absence of pumping may take decades, the extent of water level drawdown in the coalbeds and the time to recovery depend on proximity to CBM production wells, site-specific aquifer characteristics, and proximity of drawdown monitoring sites to recharge areas. The water in coalbeds used for methane extraction in the San Juan and Raton basins, and in at least some portions of the Powder River Basin, has been documented to be nonrenewable fossil water (see Chapter 2). The long-term implications of mining fossil water, or the degree to which waters may be considered fossil, have not been thoroughly studied nor included as part of the discussion of management approaches for CBM produced water.

About 83 percent of the impoundments in the Powder River Basin of Wyoming are on-channel and about 6 percent are unlined and off-channel, with intent to recharge groundwater beneath impoundments. The remaining impoundments are lined and off-channel, with the aim to reduce or prevent leakage and infiltration of CBM produced water into underlying shallow alluvial groundwater. The natural and human-influenced differences between individual impoundments—including the substrate (e.g., soil or bedrock) on which the impoundment is constructed, the volume of the impoundment and of volumes and balances[7] of CBM produced water entering the impoundment over time, the means by which CBM produced water travels to the impoundment (whether through a pipe or over land), the length of time the water is in the impoundment, and the local climate—can influence the way in which produced water stored in the impoundment may affect the groundwater beneath the impoundment. A concern is the potential for impoundments, through infiltration and percolation of CBM water, to dissolve and/or mobilize naturally occurring constituents in the underlying soil, including sulfate, selenium, arsenic, manganese, barium, and TDS.

Several studies using monitoring wells beneath impoundments and groundwater near them indicated a wide range in the relationship between impounded water and underlying groundwater, including (1) an increase in TDS, selenium, sulfate, chloride, and nitrate in groundwater beneath some impoundment facilities; (2) no apparent impact or interaction with underlying shallow alluvial groundwater for a substantial majority of impoundments studied; and (3) improved water quality beneath a small fraction of impoundments. Ongoing groundwater investigations in Wyoming by the DEQ have included nearly 2,000 CBM produced water impoundments. Of these, 170 reports from groundwater monitoring wells have been submitted as a part of operator permit compliance and exceedances of TDS, sulfate, and/or selenium groundwater standards beneath 17 impoundments have been documented. These studies and their results have led to new compliance monitoring guidelines for CBM impoundments in the state and recommendations for further studies. These guidelines were put into place in April 2010 (see Chapter 3 for further details).

SURFACE WATER

Discharges of CBM produced water to surface water and/or impoundments can affect the receiving water quality, whether perennial streams or rivers, ephemeral drainages, or surface impoundments. The effects of discharges to perennial and ephemeral streams and rivers and impoundments in terms of water quality and water volume—whether enhancements or depletions—are discussed below. Because dewatering of aquifers as part of CBM production can also potentially affect streamflows, studies of stream depletion are addressed in this section.

[7]"Volumes" refer to the total amount of water discharged and "balances" refers to the accounting of the disposition of those volumes (in reference to how much has evaporated, infiltrated, seeped, or spilled).

Effects from Discharge of CBM Produced Water to Streams and Rivers, Ephemeral Drainages, and Impoundments

Substantial documented discharge of produced water to streams and rivers occurs in the Powder River Basin. Produced water management records of the COGCC also substantiate significant direct discharges of CBM produced water to ephemeral and perennial drainages of the Colorado portion of the Raton Basin.[8] However, because of COGCC specifications regarding water management and discharge reporting, information is presently limited regarding quantitative effects of such discharges on surface water quality or quantity in the Raton Basin. Issues of concern in Colorado related to surface discharges include potential for erosion, soil damage, immersion of nonhydric vegetation, water and land discoloration, and development of algal mats. The Colorado Geological Survey is currently studying the interaction and effects of CBM production and produced water management on surface water and groundwater resources in the Purgatoire River Basin of Colorado (Ash and Gintautas, 2009).

Perennial Streams and Rivers

The concentration of CBM operations in the Powder River Basin and differences in regulation between Wyoming and Montana have generated a number of studies that have examined the potential effects of CBM produced water discharges on the Powder River and Tongue River drainages in Wyoming and Montana. The studies have largely focused on inorganic constituents or parameters, including specific conductance, sodium-adsorption ratio (SAR), nitrogen (as measured in ammonium, nitrate, and nitrite), pH, iron, potassium, sodium, chloride, fluoride, calcium, magnesium, sulfate, and bicarbonate. One set of studies has examined changes in the isotopic signature of surface waters as a means of examining the influence of CBM produced water on the Powder River. Specific measurement and analysis of organic constituents has been the subject of only one study to date. Although limited studies have examined the concentrations of organic constituents in produced water (e.g., Orem et al., 2007; see also Chapter 2), the effects of these organic compounds on surface water, groundwater, aquatic life, and riparian vegetation in the Powder River Basin have not been investigated.

Two studies by EPA Region 8 examined whether CBM production and produced water management caused significant changes in water quality in the Powder and Tongue rivers in Wyoming and Montana. Dawson (2007a) reported no statistically significant increases in specific conductance (measured by TDS) or SAR values associated with CBM develop-

[8] P. Gintautas, COGCC, e-mail conversation, December 1, 2009.

ment for the Tongue River through water year 2005. The study also noted that none of the assessed tributaries of the river met water quality standards for specific conductance either before or after CBM development. Surface water measured at the two mainstem Tongue River stations in Montana met applicable SAR and specific conductance standards before and after CBM development.

Dawson (2007b) used specific conductance and SAR data to determine if water quality in the Powder River at Moorhead, Montana, had changed since CBM production began in the Powder River Basin. When Powder River water quality data were considered in aggregate, with adjustments for wet and dry periods, no statistically significant effects on SAR and specific conductance values from CBM operations were evident. The results of Dawson's Powder River water quality analysis were influenced by variations in climatic conditions during the years of record that were available for comparison and the influence of the quality of produced water associated with historical conventional oil and gas operations prior to CBM development on Powder River water quality.

Another study by the U.S. Geological Survey (USGS) in conjunction with the Wyoming DEQ (Clark and Mason, 2007) compared long-term trends in water quality from 1975 to 1981 with those from 2001 to 2005. Concentrations were corrected for the influence of changes in flow. The researchers found statistically significant increases in SAR in the Powder River downstream of CBM produced water inputs and decreases in SAR values in the Powder River downstream of Clear Creek (due to diluting effects from a non-CBM-influenced tributary near the Montana border). However, the effects of CBM discharges on Powder River water quality were difficult to discern because of the effect of inputs from Salt Creek, a Power River tributary with traditional oil and gas operations.

A study by Wang et al. (2007) examined even longer-term water quality trends (1946–2002) at four USGS gauging stations on the Powder River in Wyoming and Montana. The researchers used statistical methods to examine trends in flow-corrected water quality before and after 1990 (the beginning of CBM development in the Powder River Basin) and found little change in salinity but statistically significant increases in sodicity as measured by SAR. The study also found smaller differences in water quality among downstream stations after CBM development and increasing differences in water quality between downstream stations and the most upstream station after CBM development began.

ALL Consulting (2008) used specific conductance and SAR data to evaluate changes in water quality and streamflow for five watersheds in the Powder River Basin with CBM development and produced water discharge. Conclusions about the effects of CBM produced water discharge were complicated by the influence of drought and by limited data at certain stream stations that preceded or postdated CBM development in the area. The study interpreted any observed changes in surface water quality as being due to prolonged drought rather than CBM production or produced water discharges.

A comparison between the major ion chemistry for the Powder River and CBM produced water by Brinck et al. (2008) showed that Powder River water and CBM produced water have similar TDS and sodium contents, but that the Powder River has lower SAR values due to higher calcium and magnesium concentrations than CBM produced water. Because the natural salinity of the river is similar or higher than the salinity measured in the CBM produced water, TDS was suggested not to be an effective tracer of produced water contributions to the Powder River by the authors.

Smith et al. (2009) evaluated changes in nitrogen compounds (ammonium, nitrate, and nitrite) in streams and rivers receiving CBM produced water discharges in the Powder River Basin. Ammonium, at concentrations in the range of 1 to 3 mg/L, is frequently present in CBM produced water at the wellhead. In unimpaired surface waters, ammonium is seldom present in concentrations exceeding 0.1 mg/L. Ammonium concentrations decreased with distance from the discharge source while concentrations of nitrate and nitrite increased downstream of discharge points. The extent of these changes in concentration varied, depending on the ephemeral channel type. Collectively, the nitrogen introduced into the Powder River from CBM sources resulted in substantial increases in total dissolved inorganic nitrogen (DIN) loads downstream of the point of permitted discharge of CBM water directly into the Powder River or into the conducting channel.

Rapid development of the CBM industry and discharges of large volumes of produced water into ephemeral and perennial streams and rivers have stimulated much interest in capabilities to track or trace produced water from the point of discharge to downstream locations. A similar interest has been expressed with regard to tracking the fate of produced water discharged to impoundments. These interests have been particularly expressed in the Powder River Basin, and recent studies of isotopes of strontium and isotope ratios of carbon have identified unique isotope signatures in CBM produced waters of the basin. These signatures, much like fingerprints, have been used to uniquely identify CBM produced water, assess connectivity and comingling of waters produced from differing coal deposits, and determine the presence of CBM produced water in surface water in the Powder River Basin (Sharma and Frost, 2008; Brinck and Frost, 2009; Frost et al., 2010). During formation of biogenic methane, ^{12}C is preferentially removed by methanogenic bacteria, leaving the dissolved inorganic carbon (DIC) of the formation water enriched in ^{13}C. The resulting high ($^{13}C/^{12}C$) ratio of DIC for CBM produced water is distinct from the ratio of the same inorganic carbon ratio ($^{13}C/^{12}C$) of surface water or groundwater which does not contain CBM produced water. For ease of comparison and explanation, the carbon isotope ratios of water samples are compared to a defined international standard ratio. The difference between the carbon isotope ratio of the sample in question and the international standard is referred to as "delta 13," with a notation of $\delta^{13}C_{DIC}$ (see Figure 5.3). Because of the relatively small differences that are measurable between the carbon isotope ratio of the sample in question and the international standard, the differences are expressed as tenths of percentages, with a notation of "per mil."

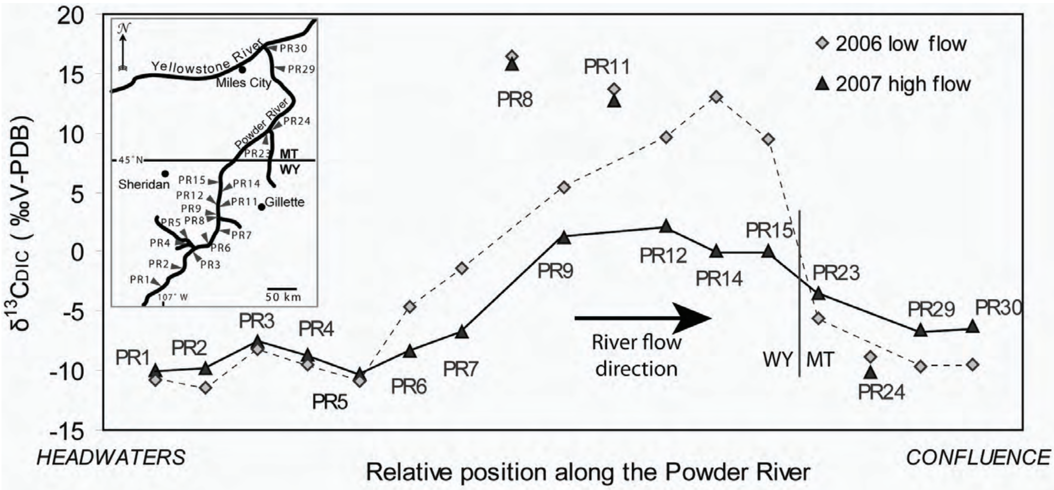

FIGURE 5.3 $\delta^{13}C_{DIC}$ values of DIC of water samples from along the Powder River and its tributaries, under low- and high-flow conditions (September 2006; June-July 2007). Locations: PR1 (farthest upstream sampling location, WY); PR30 (farthest downstream sampling location, confluence of Powder River with Yellowstone River, MT). PR8 (Beaver Creek), PR11 (Flying E), and PR24 (Little Powder River) are tributary locations. Sample sites PR1 through PR15 were located in Wyoming; all other sample sites were located in Montana. A single sample was collected at each location during the low-flow or high-flow sampling times. In total, 17 samples were collected each time—14 from the main stem and three from tributaries (samples PR8, PR11, and PR24). Note that carbon isotope signatures can only be used as a fingerprint in this way in locations where methane is produced biogenically (see Chapter 2). SOURCES: Sharma and Frost (2008), Frost et al. (2010).

Sharma and Frost (2008) found that the $\delta^{13}C_{DIC}$ for produced water samples collected from different coal zones and from different parts of the Powder River Basin were enriched in $\delta^{13}C_{DIC}$, ranging from +12 per mil to +22 per mil as a result of the biogenic production of methane, which preferentially removes ^{12}C. In contrast, water samples not influenced by CBM produced water typically have negative $\delta^{13}C_{DIC}$ values. Sharma and Frost subsequently collected water samples from the entire length of the Powder River for two different flow conditions (low and high). Values of $\delta^{13}C_{DIC}$ for all samples ranged from –11.4 per mil to +16.4 per mil, as shown in Figure 5.3. Sharma and Frost concluded that samples with significantly positive $\delta^{13}C_{DIC}$ values reflected inputs of CBM produced water.

The headwaters area of the Powder River in Wyoming, represented by sample sites PR1 through PR5, is considered upstream of CBM development. Samples from these locations had $\delta^{13}C_{DIC}$ values ranging from between –8.3 and –11.4 per mil, suggesting that the water in this section of the river was relatively uninfluenced by CBM produced water. Samples collected progressively downstream (PR6 and PR7) had $\delta^{13}C_{DIC}$ values that were less negative (−4.7 per mil and −1.4 per mil, respectively). Sharma and Frost proposed that "these values may reflect incorporation of CBNG [CBM] water discharged from production in this area." Downstream of this point (i.e., PR8 through PR15), water samples had significantly positive $\delta^{13}C_{DIC}$ values, reflecting "an area of more intense CBNG [CBM] development" and likely a predominance or relative abundance of CBM produced water in the river. The authors reported that "highly positive $\delta^{13}C_{DIC}$ of Powder River samples in Wyoming . . . from . . . (PR9 to 15) suggests the presence of CBNG [CBM]-produced water in the river related to local CBNG [CBM] production."

Again referring to Figure 5.3, the authors report that samples collected in Montana all had negative $\delta^{13}C_{DIC}$, further noting "that surface water in Montana is little to unaffected by CBNG [CBM] production during low-flow conditions." Similar patterns were observed for samples collected during high-flow conditions.

In interpreting the data for the Powder River, it is important to recognize that $\delta^{13}C_{DIC}$ values can be changed or influenced by a number of processes, including dilution by addition of another source of water with a different $^{13}C/^{12}C$ ratio, such as at the confluence of a major tributary like Clear Creek. Clear Creek discharges to the Powder River between sampling points PR14 and PR15. Below the confluence of the tributary and the mainstem of the river, the $^{13}C/^{12}C$ ratio will be somewhere between the $\delta^{13}C_{DIC}$ values of the Powder River and the tributary inflow. Thus, the change in $\delta^{13}C_{DIC}$ value between PR14 and PR23 (i.e., in crossing between the Wyoming-Montana border) reflects the diluting effect of inflows from Clear Creek, a Wyoming-originated tributary that is relatively uninfluenced by CBM produced water discharges.

Ephemeral Drainages and Impoundments

Several studies have documented increases in concentrations of TDS, sodium, and trace elements and the pH of CBM produced water that is discharged to ephemeral drainages in the Powder River Basin. Recalling that the outfall which discharges CBM produced water into an impoundment usually represents a combination of CBM product water combined from several CBM wells (see Chapter 4), water in the impoundments reflects changes in the chemistry (1) between the end-of-pipe discharge and impoundment and (2) after the water has been sitting in the impoundments. McBeth et al. (2003) assessed changes in CBM produced water composition between discharge points and associated holding ponds within the Powder River Basin. Consistent with data reported by Rice et al. (2000), they reported that pH, specific conductance, SAR, and concentrations of TDS, alkalinity, sodium, calcium, magnesium, and potassium in CBM discharge water increased significantly as discharged water traveled downgradient in ephemeral stream channels. These findings were further substantiated by Jackson and Reddy (2007).

Sodium and alkalinity concentrations and pH also tended to increase between CBM produced water outfalls and impoundments, due primarily to evaporation, while calcium concentrations decreased between outfalls and associated discharge ponds (thus increasing SAR values), due to calcite precipitation (McBeth et al., 2003; Brinck et al., 2008). Stednick and Sanford (2005) reported that CBM produced water that was discharged to ephemeral channels dissolved soluble salts in the ephemeral channel. They noted that once CBM produced water discharge stopped, TDS concentrations in these same ephemeral streams and rivers were higher than before CBM produced water was discharged to the stream channel.

Patz et al. (2006) examined the chemistry of trace elements in CBM discharge water reacting with semiarid ephemeral stream channels in the Powder River Basin. The study showed that dissolved iron and manganese concentrations decreased and arsenic and selenium concentrations increased downgradient of discharge points.

A recent study of outfalls (discharge points) and their corresponding impoundments collected in five watersheds of the Powder River Basin (the Cheyenne, Belle Fourche, Little Powder, Powder, and Tongue rivers; Jackson and Reddy, 2007, 2010; see Table 2.3) showed general increase in concentrations of trace elements from outfalls to disposal impoundments. Table 5.1 compares mean values (overall means and ranges) for constituents in CBM impoundments in five watersheds to water quality standards or criteria for drinking water, aquatic life, irrigation, and livestock watering. The overall mean levels of most constituents were within most water quality standards; only aluminum exceeded federal drinking water standards, and only aluminum and copper exceeded the aquatic life criterion (Jackson and Reddy, 2010). The upper end of the range of mean aluminum, arsenic, chromium, copper, iron, manganese, and sulfate concentrations and SAR values exceeded one or more standards in some of the impoundments. Jackson and Reddy (2010) suggested that most CBM produced waters examined in their study were unsuitable for human drinking water and aquatic life, but were suitable for agricultural uses and livestock and wildlife drinking water. The range of mean values in Table 5.1 suggests variation among watersheds and impoundments within a watershed that cannot be quantified or described through examination of simple mean values (see also Jackson and Reddy, 2010).

Stream Depletion

The committee was unable to find any published data or reports documenting measurable stream depletions due to CBM water production in the basins studied. Modeling studies have been completed to predict the amount of stream depletion resulting from CBM groundwater withdrawals within the Piceance, Raton, Northern San Juan, and Sand Wash basins in Colorado (see Chapter 2). The studies were conducted to address concerns over potential reductions in spring flows and streamflows resulting from CBM removals from "tributary" groundwater and to help identify "nontributary"[9] groundwater of the basins (see Chapter 3). The Glover-Balmer analytical solution (see Chapter 2) was used to predict the total amount of shallow alluvial groundwater drawdown that might be attributable to CBM produced water withdrawals in the basins and what impact these predicted drawdowns would have on perennial streamflows in the basins. A schematic diagram showing conceptualized connections between coalbed seams, aquifers, and surface water is shown in Figure 5.4.

Although the models estimated varying degrees of stream depletion (ranging from <1 acre-foot per year in the Piceance Basin [S.S. Papadopulos & Associates, Inc., 2007a] to 2,500 acre feet per year in the Colorado portion of the Raton Basin [S.S. Papadopulos & Associates, Inc., 2007b]), a review by the committee of the modeling studies revealed that the models were not calibrated against actual stream measurements in areas of CBM production before being applied to the subject water bodies (discussion in Chapter 2). Similarly, the general assumption of "tributary" groundwater applied in the modeling efforts is not consistent with the data from the San Juan Basin that indicated discontinuous coalbeds, limited hydraulic connection, or in some cases long distances between the deep coalbed targets for methane production and the surface. A summary of assumptions and limitations of the Glover-Balmer model assessment is included in Chapter 2.

Summary of Surface Water Studies

Several studies have assessed the presence and effects of CBM produced water discharge on perennial and ephemeral stream quality in the western CBM basins. The majority of studies on perennial drainages (Powder and Tongue rivers) used inorganic constituents, especially SAR and TDS, to discern changes in surface water quality resulting from CBM inputs. One study showed a statistically significant increase in flow-adjusted SAR values in the Powder River after CBM development began around 1990, but all other studies of the Tongue and Powder rivers that the committee was able to access found that inputs from traditional oil and gas operations and the effects of droughts made the influence of CBM development on water quality difficult to discern. This difficulty persisted even when adjustments were made in the data analyses to account for wet and dry periods. Collectively, nitrogen compounds introduced into the Powder River from CBM discharges resulted in substantial increases in total DIN loads downstream of discharge points. Carbon isotopic "fingerprinting" studies showed higher concentrations of CBM sourced dissolved inorganic carbon in the Powder River near areas of CBM production than outside the areas of production along the river. Water samples collected in Montana yielded values similar to

[9]Defined as the areas where withdrawal of groundwater by a well will not, within 100 years, deplete the flow of a natural stream at an annual rate greater than one-tenth of one percent of the annual rate of withdrawal (Wolfe and Graham, 2002).

TABLE 5.1 Comparison of Mean Concentrations of Constituents Measured in Water Samples from Multiple Impoundments Within Five Watersheds of the Powder River Basin, 2003–2005, with Relevant Water Quality Standards

Analyte	Units	Overall Mean for Samples from Surface Impoundments in 5 PRB Watersheds[a]	Range in Mean Values Measured Within Impoundments in 5 PRB Watersheds[a]	Federal Drinking Water Standard[b]	Federal Chronic/ Acute Clean Water Act Aquatic Life Criterion[c]	Agriculture Standards (Wyoming Class II)[d]	Livestock Standards (Wyoming Class III)[d]
Trace/Minor Elements							
Aluminum	µg/L	397	17.3–1,326	50–200	87/750	5,000	5,000
Arsenic	µg/L	4.84	0.75–23.2	10	150/340	100	200
Barium	µg/L	230	103–396	2,000	—	—	—
Boron	µg/L	118	65.2–184	—	—	750	5,000
Cadmium	µg/L	<1.12	<1.12	5	0.25/2.0	10	50
Chromium	µg/L	8.32	5.20–11.4	100	74/570 (Cr III), 11/16 (Cr VI)	100	50
Copper	µg/L	17.2	5.08–27.3	1,300/1,000	9.0/13	200.0	500
Iron	µg/L	271	145–462	300	1,000	5,000	—
Lead	µg/L	<2.07	<2.07	15	2.5/65	5,000	100
Manganese	µg/L	19.6	3.30–65.4	50	—	200	—
Molybdenum	µg/L	2.27	0.96–6.72	—	—	—	—
Selenium	µg/L	1.26	0.79–2.37	50	5/12.82[c]	20	50
Zinc	µg/L	11.5	8.50–18.3	5,000	120/120	2,000	25,000

Major Elements							
Alkalinity	mg/L as HCO_3	4,373	1,800–8,007	—	—	—	—
Calcium	mg/L	21.4	12.8–38.5	—	—	—	—
Magnesium	mg/L	7.00	2.92–10.2	—	—	—	—
SAR		13.5	4.9–22.8	—	—	8	—
Sodium	mg/L	182	77.9–319	—	—	—	—
Sulfate	mg/L SO_4	455	19–1,288	250	250	200	3,000
Hardness	mg/L as $CaCO_3$	82.3	44.0–138	—	—	—	—

[a]Jackson and Reddy (2007). Supplemental Information. A total of 26 sites were sampled for this study, although the number of sampling sites differed among the watersheds studied. The "overall mean" reflects the average of the values from multiple impoundments sampled in all five watersheds.

[b]EPA (2009a)—Safe Drinking Water Act maximum contaminant levels and secondary maximum contaminant levels. Values for aluminum, copper (1,000 μg/L), iron, manganese, and zinc are secondary maximum contaminant levels.

[c]EPA (2009b)—for dissolved metals, using a hardness of 100 mg/L for hardness-sensitive metals (copper, cadmium, zinc). Criterion value for selenium is proposed; assumes all selenium is present as selenate.

[d]Wyoming DEQ (2005).

NOTE: Aquatic life criterion values for hardness-dependent metals (copper, cadmium, lead, zinc) were calculated assuming a hardness of 100 μg/L as calcium carbonate ($CaCO_3$). SAR = sodium adsorption ratio.

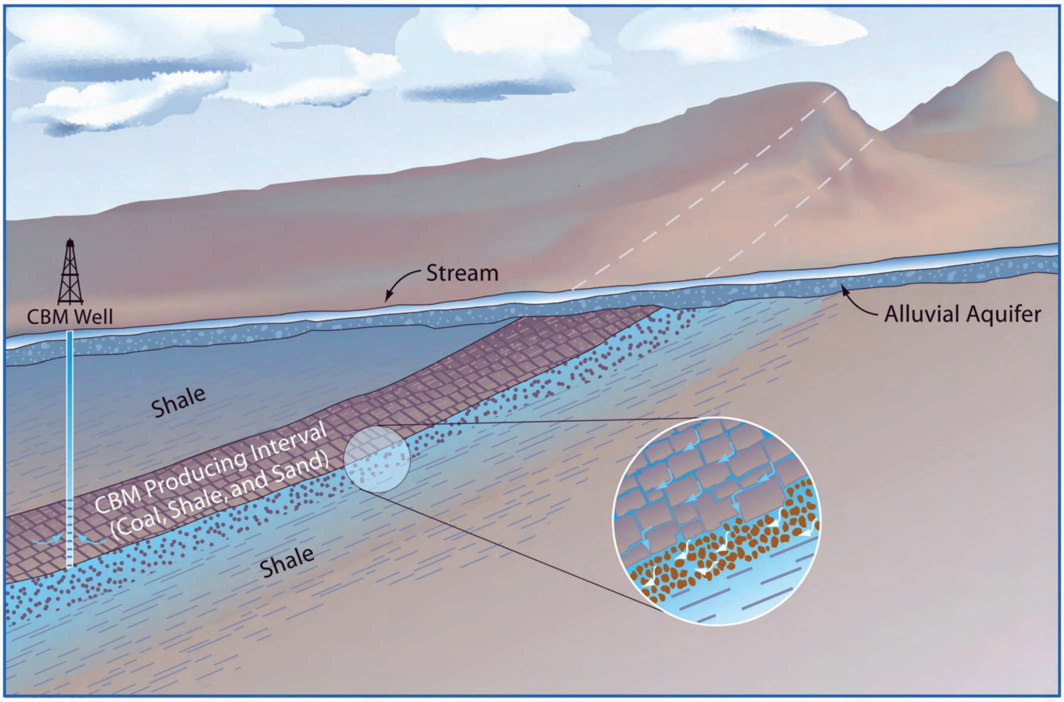

FIGURE 5.4 Conceptualized schematic showing potential hydrological connection between CBM well, water within CBM bearing aquifers, and surface water. SOURCE: Colorado Geological Survey, available at geosurvey.state.co.us/Portals/0/CBM-SJB-diagramweb2.jpg.

the expected value for uninfluenced native surface water or groundwater, suggesting dilution of CBM water within the Powder River in Wyoming by tributary inflows near the Montana-Wyoming border.

Two studies of water quality in ephemeral streams have demonstrated that pH, specific conductance, and SAR values and concentrations of TDS, alkalinity, sodium, calcium, magnesium, potassium, arsenic, and selenium in CBM discharge water increased as discharged water traveled downgradient in ephemeral stream channels, while iron and manganese concentrations decreased. Once CBM produced water discharge stopped, TDS concentrations in these same ephemeral streams were higher than before CBM produced water was discharged to the stream channel. A study of discharge water quality and the quality of water in receiving impoundments in five watersheds of the Powder River Basin showed a general increase in concentrations of trace elements from outfall to disposal impoundments.

Stream depletion studies have involved only theoretical modeling, conducted for the Piceance, Raton, Northern San Juan, and Sand Wash basins in Colorado. These modeling efforts have not yet been calibrated against actual stream measurements in areas of CBM production. Similarly, the general assumption of "tributary" groundwater as a part of the conceptual model does not comport with the geochemical, geophysical, and geological data available from the San Juan Basin, which indicate discontinuous aquifers and long travel times between the deep coalbed targets of methane production and the surface.

SOIL QUALITY AND AGRICULTURAL PRODUCTION

Potential and realized adverse effects of salinity and sodicity of irrigation water on agricultural production and soil quality have been extensively documented for at least 60 years (Richards, 1954; Ayers and Westcot, 1994). Elevated sodicity has the potential to cause soil quality deterioration, or "soil dispersion," which is the breakdown of aggregated soil clods into individual particles, and an associated loss of water- and gas-conducting pores and channels in the soil. Soil dispersion often leads to measurable reductions in water infiltration rates, which ultimately leads to salinization, or accumulation of the salt content of soil to above-normal levels.

Soil Quality

Potential effects of produced water on agricultural landscapes have been investigated extensively in the Powder River Basin. Browning et al. (2007) reported that soils repeatedly wetted with simulated Powder River Basin CBM produced water resulted in significant changes in chemical and physical properties over time, despite incidental simulated rainfall events. Irrigated soils, dominated by clay-sized particles, had consistent increases in water-holding capacity, leading to water-logged characteristics, while drought-prone soils (coarse-grained) lost their water-holding capacity, thereby rendering the soils even more prone to drought. Vance et al. (2008) reported that CBM produced water can cause modification of soil density and aeration, low plant-available water capacity, low hydraulic conductivity, increased swelling, and uneven soil wetting. Application of CBM produced water from the Powder River Basin over multiple years increased soil electrical conductivity (EC) and SAR to depths of 30 centimeters. Irrigation with CBM produced water also reduced surface infiltration rates and subsurface flow rates in the top 120 centimeters (Vance et al., 2008).

Bauder et al. (2008) observed soil solution salinities exceeding 3,000 µmhos/cm and SAR values of approximately 12 following simulated flood irrigation with CBM produced water, subsequently followed by simulated single rainfall events. They concluded that sodium-induced dispersion of fine-textured soils is likely to occur from application of CBM produced water to some agricultural fields in the Powder River Basin. Research by Ganjegunte et al. (2005) and Johnston et al. (2007) led the authors to conclude that CBM waters in the northwestern portion of the Powder River Basin, where salinities and SAR values are higher than those studied by Bauder and Brock (2000), were generally not suitable for direct land application.

Numerous research efforts have focused on producing definitive characterization of the impact of waters of various SAR on soil quality. The principal soil characteristic which has been investigated has been either infiltration or soil hydraulic conductivity. Suarez et al. (2006) reported that for some soils (loam, a soil having relatively uniform proportions of sand, silt, and clay), adverse impacts of sodium on infiltration when applied water had a SAR greater than 2, while for a dispersive clay soil adverse impacts occurred above SAR of 4. In both soils the SAR behavior was similar for water having a TDS concentration of approximately 640 or 1280 mg/L, indicating that in this range TDS did not affect infiltration. Reductions in infiltration were evident during irrigation and rain events, with lower infiltration during the rain simulations. In an earlier and similar study, Mace and Amrhein (2001) reported that irrigation with water having SAR 5 and 8 resulted in irreversible plugging of soil pores by dispersed clay, as well as internal swelling.

Plant Growth and Survival

Vance et al. (2008) examined the effects of irrigation with CBM produced water on soils and plants of the Powder River Basin by comparing soil and plant conditions following various irrigation practices with those from nonirrigated sites. Irrigation with CBM produced water significantly increased the production and cover of native perennial grasses, but overall plant community diversity and uniformity of species across the landscape decreased. The researchers concluded that adverse changes in soil quality with CBM irrigation can restrict plant growth and cause plant water stress. Salinity has the potential to have significant impact on plant communities, plant community sustainability, and livestock and wildlife forage compatibility (Soil Improvement Committee, 1995). High salt content of soil pore water can also reduce the availability of water for plants and cause agricultural crops to expend more energy extracting water from the root zone than would be required in the absence of elevated salinity in the soil water (Arthur et al., 2008).

Prospects for Produced Water Irrigation

Many studies on the effects of using CBM produced water for irrigation demonstrate the challenges associated with directly putting CBM produced water to beneficial use in agricultural fields via surface irrigation or land application. Although the response of clay-rich soils to CBM produced water is not universal, the use of most CBM produced waters for irrigation, especially in smectite[10] clay-rich soils, could reduce infiltration and may require intensive management, including selection of crops to be irrigated, timing and amount of produced water applied, and the use of soil amendments. Use of CBM produced water for irrigation appears practical and sustainable, with various combinations of selective application to nondispersive soils, treatment, dilution or blending of CBM produced water with other water sources, amendment of produced water and soils to be irrigated, and appropriate timing of irrigation practices to take advantage of ameliorating effects of rainfall and snowmelt. After use of CBM produced water ceases, additional soil management, including soil amendments,[11] may be required to restore soil agricultural resources to pre-CBM water application conditions.

Much of the actual practice of applying CBM produced water to landscapes is limited to industry's efforts—largely on industry-owned land or land for which the industry has paid a rental or lease fee—and application of CBM produced water to landscapes or for irrigation is not a widespread practice at present. Nonetheless, challenges to WYDEQ-issued permits to manage CBM produced water through direct applications to land have been raised by several landowners, environmental groups, scientists, and the EPA. These issues are still being scientifically documented and analyzed (see also section later in this chapter on "Registered Citizen Complaints") and speak toward the infancy of the CBM industry (see Chapter 1) and of the rules, regulations, and policies being applied to CBM produced water management, particularly in Wyoming, as they related to surface discharges.

ECOLOGICAL EFFECTS

In this section, potential and observed ecological effects of CBM produced water on aquatic life and riparian habitats are discussed. Few on-site, in situ, or real-time studies have been completed and published on this topic, specific to the study area of this report. Many of the studies involve laboratory experiments that have neither employed water with chemistry in concert with average CBM produced water chemistry nor been verified against field studies. The committee provides an overview of this topic and suggests areas for further examination.

[10]Smectite is a group of clay minerals composed of layers of aluminum ions which lie between silicon-oxygen sheets. These kinds of clays have the ability to absorb water molecules between the sheets, allowing the mineral structure to expand.

[11]Soil "amendments" such as gypsum, organic matter, and elemental sulfur may be added to agricultural soils to liberate sodium. This release of sodium, accompanied by a supply of calcium, enhances improvement in soil structure, and sodium-affected soils can be restored to agricultural productivity. Soil amendments are sometimes called "soil conditioners."

Toxicological Effects on Aquatic Biota

CBM produced waters typically contain numerous chemical constituents (see Table 5.1), several of which are potentially toxic to fish, macroinvertebrates, and other aquatic organisms, when concentrations exceed toxicity threshold levels for these organisms. Stressors (whether described as constituents or contaminants that put stress on target species) of primary concern associated with CBM discharges include aluminum, arsenic, barium, beryllium, iron, manganese, and selenium, increased turbidity and TDS. Recent studies have also examined the toxicological effects of sodium bicarbonate, an ion of abundance in most CBM water. Most published research investigating these stressors indicates that increases in TDS have the greatest potential for direct toxicological impacts in receiving streams and rivers (Boelter et al., 1992; Confluence Consulting, 2004; Davis et al., 2006; Skaar et al., 2006; Farag et al., 2010). Recent studies have shown considerable variation in the toxicity of TDS due to the difference in relative concentrations of specific ions comprising TDS (Mount et al., 1997; Dwyer et al., 1992). Specific ionic composition will also change seasonally and among watersheds (Pillard et al., 1999). Details of existing laboratory studies on the effects of TDS, of interactions between elevated TDS and other stressors, of sodium bicarbonate on organisms, and of field studies on the effects of CBM produced water on organisms are outlined in subsequent sections.

TDS as a Measure of Toxicity

Many freshwater organisms are highly sensitive to changes in salinity, and discharge of high TDS effluents into receiving systems may result in physiologically stressful conditions due to alterations in osmotic conditions. Most of the available research on sensitivity to TDS and salinity used laboratory toxicity tests to predict responses of fish and macroinvertebrates and focused on conventional test species. These studies are used to understand the potential significance of various constituent concentrations to organisms. In laboratory tests on standard test organisms, major ions such as chlorine, bicarbonate, sulfate, sodium, calcium, magnesium, and potassium in combination with elevated TDS have been found to be toxic to some aquatic species (e.g., Goodfellow et al., 2000; Goetsch and Palmer, 1997; Pillard et al., 1999; Dickerson and Vinyard, 1999; Chapman et al., 2000; Soucek, 2007).

Relatively few studies have been conducted with species relevant to the study areas in the western states and with a specific focus on CBM produced water. Among these studies, Chapman et al. (2000) measured toxic effects of TDS in the laboratory on benthic macroinvertebrates (chironomids) and rainbow trout at concentrations similar to those in CBM produced water. Although trout showed tolerance to TDS at concentrations >2,000 mg/L, benthic macroinvertebrates were significantly affected at TDS concentrations of

1,100 mg/L. Mayflies were found to be sensitive to sodium, with LC50[12] values of approximately 900 mg/L TDS. Chapman et al. also reported that aquatic organisms with no history of high-TDS exposures could be able to tolerate TDS concentrations of at least 1,000 mg/L.

In a study predating CBM development in the Powder River Basin, Boelter et al. (1992) conducted laboratory toxicity tests with produced water collected downstream from the Salt Creek oil fields. Salt Creek is a headwaters tributary of the Powder River. Salt Creek was primarily impacted by traditional oil and gas development at the time of the study with produced water, therefore, of different composition than CBM produced water. This difference notwithstanding, results of this study have potential relevance to CBM produced water disposal in streams and rivers because the researchers isolated the toxicological effects of major ions that are present in oil, natural gas, and CBM produced waters. The data reported by Boelter were used to complete toxicity identification and evaluation analysis, an empirical procedure designed to identify specific sources of toxicity in complex effluents. The analysis revealed that toxicity, if it was to occur, would have been primarily a result of sodium, chlorine, bicarbonate, and carbonate concentrations in combination. In reality, the predictability of toxicity of CBM produced water to aquatic organisms is complicated by (1) variations in geochemical characteristics of CBM produced water among geographic regions and basins (see Chapter 2) and within a single watershed (Van Voast, 2003), (2) the timing of produced water discharges, (3) the receiving stream's quality and flow conditions, (4) the degree of instream mixing and dilution, and (5) the diversity of biological agents among basins.

Exposure to one stressor (contaminant) may increase susceptibility of aquatic species to other stressors (Clements, 1999; Paine et al., 1998). Pertinent to CBM discharges, research has shown that some contaminants are more toxic under conditions of high TDS than when found in water having relatively low TDS concentrations (see e.g., Chapter 2, Table 2.2). Additionally, the converse has been reported in the scientific literature—that is, the presence of some specific contaminants may exacerbate toxicity associated with elevated TDS concentrations (Anderson et al., 1994; Hall et al., 1994; Dickerson and Vinyard, 1999). Pillard et al. (1999) recommended that potential interactions between high-TDS effluents and other stressors (contaminants) be closely considered during CBM exploration and development, because a variety of physical and chemical stressors may be introduced into watersheds during the development and production periods.

Additionally, long-term alterations in streamflow may influence the effects of discharges from CBM on aquatic ecosystems. Boelter et al. (1992) reported that toxic effects of discharges from oil fields in Salt Creek drainage were greater and extended much farther downstream in the Powder River during periods of low-flow conditions.

[12]LC50 is defined as the concentration that resulted in 50 percent mortality of test species.

Mount et al. (1997) developed statistical models to predict water quality toxicity to fish and invertebrates using specific concentrations of major ions. Based on these models and assumptions of direct exposure of study species to undiluted CBM produced water, produced waters from many CBM sites within the study area in the Powder River Basin could be toxic to aquatic organisms. For example, employing the Mount et al. model and using data for water samples representing median (50th percentile) ionic characteristics of samples collected from the Wasatch and Fort Union aquifers in Wyoming (Bartos and Ogle, 2002; see Figure 5.5), the committee calculated that the mortality of fathead minnows exposed to undiluted CBM produced water of composition similar to that reported by Bartos and Ogle would be approximately 20 percent (see Table 5.2). Predicted mortality would increase to approximately 60 percent if organisms were directly exposed to undiluted CBM produced water representing the upper 75th percentile of the samples. These predicted values of mortality were based on mean concentrations of potassium, bicarbonate,

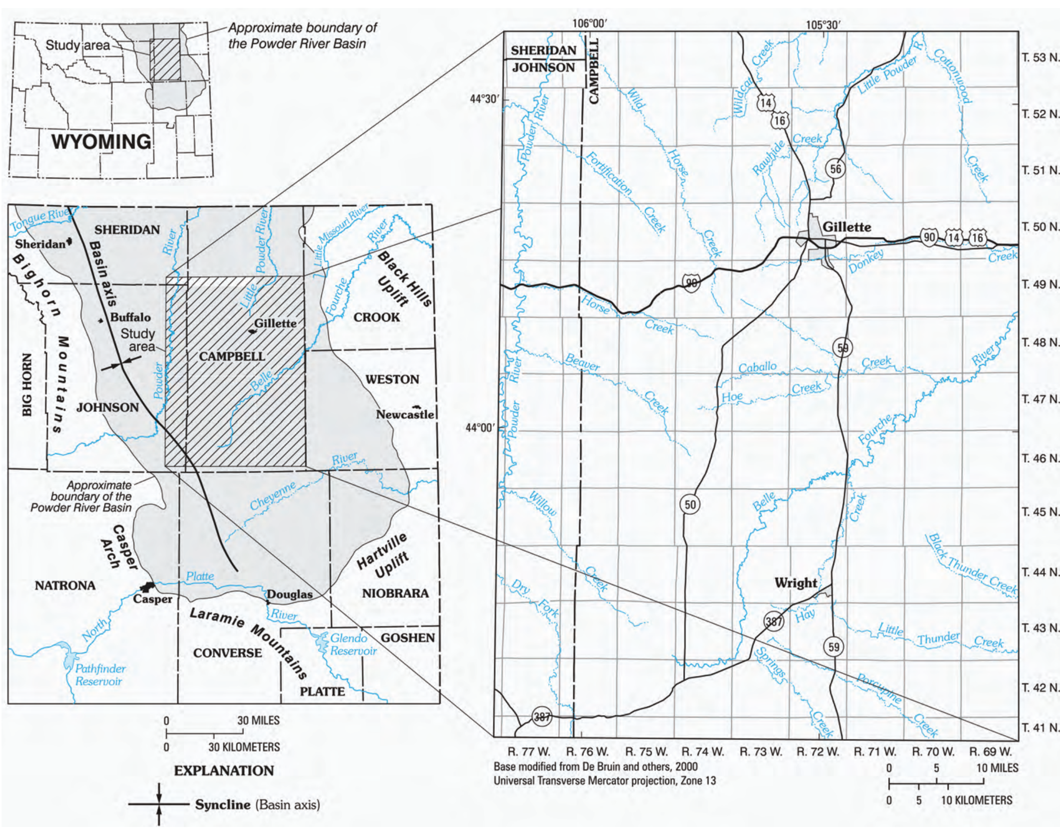

FIGURE 5.5 Map showing location of the study area in the Powder River Basin, Wyoming. SOURCE: Bartos and Ogle (2002).

TABLE 5.2 Predicted Mortality of Fathead Minnows (*Pimephales promelas*) Exposed to Water Quality Composed of Constituents and Concentrations Represented by Mean Concentrations from CBM Water Samples.

	Constituent Concentrations (50th and 75th percentiles) of 13 Combined Water Quality Samples from Wasatch and Fort Union formations		Constituent Concentrations of Water Quality (single samples collected from 3 CBM wells)		
Parameter	50th Percentile Concentration	75th Percentile Concentration	W5	W6	C11
Potassium (mg/L)	12	13	14	13	48
Magnesium (mg/L)	15	28	270	24	39
Chloride (mg/L)	9	14	17	0.3	21
Sulfate (mg/L)	0.5	1	2,700	10	0.3
Bicarbonate (mg/L)	712	1,103	326	1,244	3,134
TDS (mg/L)	644	959	4,020	1,010	2,720
Conductivity (μmhosm)	1,070	1,610	4,330	1,850	4,180
Predicted mortality (percent)	20.3	60.4	45.3	73.6	100

NOTE: Samples were collected from the Wasatch and Fort Union Formations, Eastern Powder River Basin, Wyoming. Samples W5 and W6 are wells located in the Wasatch aquifer. Sample C11 is from the Wyodak-Anderson coal zone (Fort Union formation).
SOURCES: Analytical data from Bartos and Ogle (2002); predicted mortality based on model in Mount et al. (1997); toxicity test protocols followed EPA (2002); calculations completed as part of this study.

magnesium, chlorine, and sulfate found in CBM produced water from the Wasatch and Fort Union formations from the eastern Powder River Basin in Wyoming.

Data from three specific water quality sampling sites (W5, W6, C11) are shown in Table 5.2 to illustrate the potential for variations in ionic composition, TDS, and predicted mortality among three sampling site conditions. The calculations for mortality results in the table are based on the assumption of direct and prolonged exposure to undiluted, untreated CBM produced water. The calculations did not include sodium and calcium concentrations because they were not available for use in the model. Data in Table 5.2 show that despite a fourfold greater TDS and a twofold greater conductivity at site W5 than at site W6, predicted toxicity associated with water at site W5 was considerably less than that for site W6. The predictability of toxicity of TDS is likely also complicated by unknown effects of interactions among individual ions. Because the estimated toxicity of these high TDS effluents was based on laboratory results, the direct relevance of these findings to field conditions is somewhat uncertain. However, the results indicate that high TDS effluents have the potential to be highly toxic to standardized test organisms under controlled conditions.

Certain limitations to the application of these modeling and laboratory studies to examine the effects of CBM produced water include (1) the use of mean concentrations and discharges in a system with natural geochemical and hydrogeological variability; (2) the fact that permitted discharges of CBM produced water in many cases require treatment before discharge as well as a defined mixing zone (zone of mixing between CBM produced water and receiving water that dilutes the concentration of the CBM water; see Chapter 3 for details), leaving a small likelihood of direct exposure to undiluted CBM produced water; (3) ionic concentrations in surface water that vary with stream discharge and may increase during the beginning of storm and snowmelt events and during low-flow conditions (Sharma and Frost, 2008). CBM produced water may comprise a significant portion of total stream discharge during periods of low summer flow, and concentrations of major ions may vary during these low-flow periods. These temporal patterns of stream discharge and conductivity also depend on the source of water. For example, streams and rivers that originate in the mountains typically show a single peak in discharge during spring runoff (Clark et al., 2001). In contrast, streams and rivers originating in the plains are much more variable and may have little or no flow during late summer to early winter.

Laboratory Studies on Toxicity of Sodium Bicarbonate

The USGS examined acute and chronic toxicity of sodium bicarbonate to fathead minnows (*Pimephales promelas*), a standardized test species used in aquatic toxicology studies (see Table 5.2; Skaar et al., 2006; Farag et al., 2010). Laboratory tests simulating water characteristics in the Powder and Tongue rivers implicated bicarbonate, rather than sodium, as a cause of significant acute toxicity to the minnows (Farag et al., 2010). The study additionally included assessment of responsiveness of other fish species, amphibians, and invertebrates (see Table 5.3). As shown in Table 5.2, the 50th and 75th percentile concentrations of bicarbonate from groundwater samples collected from the Powder River Basin were 712 mg/L and 1,103 mg/L, respectively. Minnow survival was significantly lower in all treatments having sodium bicarbonate concentrations exceeding 400 mg/L (291 mg/L bicarbonate) and was reduced from 89 percent survival in controls to 2.4 percent at sodium bicarbonate concentrations of 1,400 mg/L (1,017 mg/L bicarbonate). Researchers also reported that the incidence of gill lesions and kidney damage increased as sodium bicarbonate concentrations and exposure time increased.

Acute LC50 values for several fish species after 96 hours of exposure to treatment water ranged from 1,158 to 5,526 mg/L sodium bicarbonate (841 to 4,014 mg/L bicarbonate), with significantly greater effects on younger fish (Table 5.3). Results also showed that an

TABLE 5.3 Results of Acute and Chronic Toxicity Tests Showing Effects of Sodium Bicarbonate on Fish, Amphibians, and Invertebrates.

	Acute Tests			
Species	Age of Test Species (posthatch)	Endpoint Measured	Mean LC50[a] for $NaHCO_3$ (mg/L)	Equivalent HCO_3^- LOEC[b,c] (mg/L)
Fathead minnow	4 days	Survival	1,643	1,118
Pallid sturgeon	4 days	Survival	1,158	788
Chironomus	4 days	Survival	7,920	5,391
Fathead minnow	2 days	Survival	1,793	1,220
Pallid sturgeon	4 days	Survival	1,828	1,244
Hyallela azteca	4 days	Survival	6,384	4,345
African clawed frog	4 days	Survival	1,700	1,157

	Chronic Tests			
Species	Length/Type of Test	Endpoint Measured	$NaHCO_3$ LOEC[c] (mg/L)	Equivalent HCO_3^- LOEC[b] (mg/L)
Fathead minnow	60 days	Survival	500	340
White sucker	53 days	Growth	450	306
Ceriodaphnia	7 days	Reproduction	510	347
African clawed frog	Modified FETAX embryos	Malformations	1,108	754

[a]LC50 is defined as the concentration that resulted in 50 percent mortality of test species.

[b]LOEC is the lowest observed effects concentration (higher concentrations resulted in adverse effects noted in Endpoint Measured).

[c]For comparison to bicarbonate values in CBM produced water and the Powder River (Table 5.1).

SOURCES: Skaar et al. (2006); Farag et al., 2010.

amphibian species (African clawed frog) was highly sensitive to sodium bicarbonate (LC50 = 1,700 mg/L or 1,235 mg/L bicarbonate). However, acute toxicity was much lower for two of the invertebrate species tested (*Chironomus* and *Hyalella*), with LC50 values ranging from 6,384 to 7,920 mg/L sodium bicarbonate (4,637 to 5,753 mg/L bicarbonate).

Chronic (longer-term) toxicity was observed for fish and invertebrates at much lower sodium bicarbonate concentrations, with lowest observed effect concentrations (LOECs) ranging from 450 to 510 mg/L sodium bicarbonate, or 327 to 370 mg/L bicarbonate. These laboratory findings are relevant to the Powder River Basin because the median concentration of bicarbonate in produced water from CBM wells is 712 mg/L and concentrations can exceed 3,000 mg/L (see Table 6 in Bartos and Ogle, 2002). In situ toxicity tests conducted in several tributaries of the Powder and Tongue rivers showed significant mortality when levels of sodium bicarbonate exceeded these laboratory thresholds. However, the committee notes that these values reflect effects under circumstances of direct exposure to 100 percent CBM produced water; this situation would be unlikely in perennial waters because of permitted discharge requirements.

Field Assessments of CBM Produced Water Effects

A comprehensive assessment of the potential impacts of CBM discharges on aquatic communities is currently being conducted by the USGS and the Powder River Aquatic Task Group (ATG), a consortium of state, federal, and nongovernmental organizations (Peterson et al., 2009; Farag et al., 2010). The ATG is conducting aquatic and riparian habitat analyses and field surveys of algae, macroinvertebrates, fish, amphibians, and reptiles. Data were collected from 47 locations in the Powder River Basin in 2005 and 2006, with the primary goal of the study to establish current conditions for habitat and aquatic communities in the basin and to quantify the relative influences of stream habitat conditions and water quality characteristics on aquatic communities.

Electrical conductivity of collected water samples was determined to be an important predictor of ecological conditions. Conductivity levels at the points of sampling in the Tongue River were considerably lower than in the Powder River, and species richness showed little variation among sampling sites along the Tongue River. Preliminary results of macroinvertebrate studies showed that macroinvertebrate community composition was best described by a model that included drainage area, streamflow, site location, substrate embeddedness, and specific conductance. Peterson et al. (2009) concluded that the observed longitudinal variation in fish communities from upstream to downstream in the Powder River likely resulted from a complex interplay of habitat, water quality, streamflow, and migration patterns, while much of the spatial variation in aquatic communities among the study sites (e.g. Powder River versus Tongue River) was due to broad geographic factors (e.g., stream headwaters located in mountain versus plains areas) or longitudinal changes.

Collaborative field studies conducted by the BLM, the Montana Cooperative Fishery Unit, Montana State University, and USGS characterized the impacts of CBM on the distribution of fish communities in the Powder River Basin.[13] Investigators assessed longitudinal distribution and temporal patterns of fish communities at 57 sites within the basin in 2005. A total of 24 fish species was collected, with zero to eight species collected from streams and rivers that received CBM produced water discharges and one to 12 species in streams and rivers that did not receive CBM produced water ("control" streams and rivers). Differences in the number of species and community composition in streams and rivers assessed were thus examined against the locations of CBM produced water discharges. Some

[13]See "Task 7" at www.netl.doe.gov/technologies/oil-gas/Petroleum/projects/Environmental/Federal_Lands/15467Task2.html (accessed February 24, 2010).

species were found only in streams and rivers receiving CBM produced water discharges, while other species were found exclusively in streams and rivers to which no CBM produced water had been discharged. Researchers noted considerable uncertainty regarding using the data to assess the direct effects of CBM discharges on fish assemblages.

Instream toxicity studies were conducted by researchers at the University of Wyoming to assess potential toxic effects of CBM produced water on fish (Heath and Meyer, 2008). Researchers concluded that, despite elevated concentrations of ammonia and bicarbonate, acute toxic effects were mitigated by mixing of produced water with instream flows and by biogeochemical interactions between CBM produced water and sediments in the stream (discussed previously).

Effects on Riparian Environments

Riparian areas are the interface between dry uplands and water bodies. These areas are generally vegetated by hydrophilic plant communities and potentially contribute substantially to the ecological and environmental functionality and stability of ephemeral and perennial water courses. Numerous studies have investigated the actual or potential effects of discharge of CBM produced water on riparian environments (e.g., Busch and Smith, 1995; Vandersande et al., 2001; Glenn and Nagler, 2005; and Smith et al., 2009).

Typically, the effects of CBM produced water discharge on riparian environments are a consequence of changes in the hydrology (frequency, duration, availability, or quantity of water) and the chemistry (mainly salinity) or soil substrates of the receiving stream (stream bottom, channel, and shoreline). The primary potential or observed adverse effects of CBM discharge to streams and rivers and riparian systems are (1) changes in the timing and amount of streamflow, (2) increased stream bank erosion and instability, (3) increased suspended sediment concentrations and/or turbidity, (4) downstream sediment deposition, (5) changes in riparian plant communities, and (6) increased stream water and sediment salinity. Studies of these effects are discussed in the following sections.

Ephemeral Drainages

The lower and less frequent flows of ephemeral streams compared to perennial streams and rivers can result in greater expression of adverse effects of CBM discharges on the hydrology and water quality of the ephemeral drainages than perennial streams and rivers. As early as 2001 the Montana DEQ expressed concern about the potential effects of sustained discharges of CBM produced water to ephemeral streams. Regele and Stark (2001) proposed that CBM produced water discharges could destroy vegetation in stream channels, increase erosion and deposition of sediment in streams and reservoirs, and degrade water quality. Consequently, algae, aquatic invertebrates, fish, amphibians, and other biological aspects of streams and rivers could be adversely affected. The study further proposed that ephemeral streams may become enlarged and potentially change into perennial streams and rivers while receiving CBM produced water discharge. Arthur et al. (2008) proposed that changes in hydrological regime could modify conditions for plants and animals living in the riparian corridor and could lead to adverse environmental impacts.

Although baseline information on flows in ephemeral drainages is generally not available, substantial evidence has shown that regulated, controlled, and managed or unmanaged and/or unregulated[14] dynamic alteration in streamflow can result in bank scouring, bottom sedimentation, and increased erosion (Farag et al., 2010; Browning et al., 2005; Maxson and Campbell, 1935). The committee was not able to find published evidence of any widespread effects of this nature in ephemeral streams and gullies receiving CBM produced water discharges. However, at least two instances of land alteration downstream from CBM discharges in ephemeral channels have been documented and are discussed later in this chapter.

Riparian Vegetation

Studies have documented the adverse effects of increased salinity of riparian soils and changes in the natural hydrograph on native riparian vegetation in the southwestern United States. Changes in stream hydrology or salinity generally will result in gradual changes in riparian plant communities (Kirkpatrick et al., 2006). The more saline the soil in riparian areas, the more difficult for plants to extract nutrients and grow (Stearns et al., 2005). Increases in stream salinity or conditions of prolonged or sustained saturation of bank and floodplain sediments generally lead to plant communities dominated by salt-tolerant species. In many instances these species are nonnative.

Stearns et al. (2005) investigated effects of CBM discharge waters on native and introduced vegetation density and diversity in ephemeral drainages in the Juniper Draw Basin in Wyoming. Coulees and ephemeral channels receiving produced water in the Powder River Basin had greater percentages of nonnative plant species than did similar coulees and ephemeral channels not receiving produced water. Stearns et al. concluded that CBM produced water discharge could threaten established native vegetation by invasion of and competition by salt-tolerant species. The invasion of nonnative species, such as may occur in association with CBM produced water discharge, presents challenges for land managers (e.g., Bergquist et al., 2007). Native species provide cover and native wildlife habitat that

[14]"Unmanaged" encompasses uncontrolled discharge events such as seepage and leaks from impoundments, especially on-channel, discharges resulting from over-topping of impoundments due either to faulty equipment or influxes from upstream rainfall events, and dam failures. "Unregulated" refers to CBM produced water discharges without appropriate permitting. Neither term carries with it any judgment as to intentional or unintentional discharge.

nonnative vegetation does not, and the invasion of nonnative species may include noxious weeks and can alter ecosystem function.

Summary of Ecological Effects

Stressors—constituents or contaminants that put stress on species—of primary interest with respect to CBM produced water discharges into perennial or ephemeral streams or impoundments include several trace elements, TDS, bicarbonate and other ions such as potassium and chloride, and increased turbidity in water due to changing flow with input of CBM water. Of these factors, studies have indicated that increased TDS appears to have potential for greatest direct toxicological impacts to organisms in receiving streams and rivers. Published laboratory studies of TDS and bicarbonate effects on organisms, studies in the field of the effects of CBM produced water on organisms, and interactions between elevated TDS and other stressors and their effects on organisms have all been examined. Because few discharges occur outside the Powder River Basin, most studies have focused on this area.

Laboratory studies regarding TDS and other major ions indicate that exposure to elevated concentrations of one or more constituents can be toxic to some freshwater organisms. The committee's calculations using simple published models to predict water quality toxicity to fish and invertebrates using major ions also indicate that undiluted CBM produced water from many sites within the Powder River Basin could be toxic to many aquatic organisms. Importantly, these results are based on mean concentrations and discharges and on direct and prolonged exposure to undiluted, untreated CBM produced water or its constituents on conventional laboratory test species. In the field, permitted discharges of CBM produced water often require treatment and a defined mixing zone (mixing between CBM produced water and receiving water) within close instream proximity to discharge points. Testing most of the laboratory results against field studies and with species relevant to the study areas in the Powder River Basin has not yet been completed. To date, interactive effects relevant to CBM produced water—whereby exposure to one contaminant or stressor might increase susceptibility to others—also have not been studied.

Laboratory tests examining the acute and chronic toxicity of sodium bicarbonate implicated bicarbonate rather than sodium as a cause of acute toxicity to fathead minnows. Laboratory tests with bicarbonate on other species, including amphibians and invertebrates, exposed to undiluted CBM produced water also show acute to chronic toxicity for some of these organisms. In situ (field) tests conducted in the Tongue and Powder rivers showed mortality to some species when levels of bicarbonate exceeded laboratory toxicity thresholds. However, these results were the result of direct exposure to undiluted CBM produced water, a situation that would be unlikely for prolonged periods in perennial waters where fish are found because of: (1) permitted discharge requirements; (2) the use of the mixing zone in the calculation of the discharge allowance; (3) the geographically limited extent of undiluted CBM produced water within a receiving stream once the produced water has entered the mixing zone; and (4) the relative mobility of fish and other aquatic organisms in perennial streams and rivers.

Few field assessments have investigated the effects of CBM produced water discharges on aquatic communities. Field assessments are difficult to conduct because of the lack of baseline information prior to CBM activity in the area; thus, observed changes to aquatic or riparian communities have been difficult to attribute directly to CBM related discharges. Studies of this nature are also complex to conduct and interpret because of the interactions and overlap between habitats, water quality, limited length of time to complete studies involving community transitions that might occur over extended periods of time, and species migration. A comprehensive assessment is currently being conducted by a consortium of state, federal, and nongovernmental organizations to establish current conditions for habitat and aquatic communities for the Powder River Basin. These data will be used to measure and monitor future changes. Another field study that examined differences in the number and composition of species in perennial streams and rivers across an entire watershed against numbers of CBM discharges in those streams and rivers noted difficulty in determining any direct effects of CBM discharges on fish assemblages. An instream toxicity study to assess potential toxic effects of CBM produced water on fish concluded that, despite elevated concentrations of ammonia and bicarbonate, acute toxic effects were mitigated by mixing of produced water with natural instream flows.

Various studies have proposed several primary adverse effects of CBM discharge to ephemeral drainages and their riparian systems. These potential effects include changes in the timing and amount of streamflow, bank erosion and instability, turbidity and increased sediment concentrations or deposition, and increased salinity of the soil, all of which may affect riparian plant communities. One study that directly examined the effects of CBM discharge waters on native and introduced vegetation in ephemeral drainages in Wyoming found greater percentages of nonnative plant species in channels receiving produced water than in those that did not receive CBM water. However, baseline data in ephemeral drainages are not widely available, so these potential and observed effects on riparian communities have not yet been substantiated with more rigorous studies.

REGISTERED CITIZEN COMPLAINTS, LITIGATION, AND PUBLIC CONCERNS HEARD BY THE COMMITTEE

Citizen complaints related to CBM activities are cataloged and investigated by several states with CBM production. In this section the general types of citizen complaints filed with state agencies are reviewed, using Colorado and Wyoming as examples. Also identified are instances of landowning citizens bringing complaints to court. In addition to the review of citizen complaint information in Colorado and Wyoming, the committee heard concerns from citizens and citizen groups about the effects of CBM production at its Denver meeting in March 2009.[15]

The COGCC maintains an electronic database of complaints on the Colorado Oil and Gas Information System (COGIS).[16] Some level of investigation is completed on all claims. The database contains over 10,000 entries and allows searches for notices of alleged violations, complaints, and spills or releases. The database does not provide summaries of available information. Additionally, it is not possible to search specifically for complaints regarding impacts from CBM wells because the system aggregates all complaints pertaining to oil and gas wells. However, searches can be narrowed by qualifiers such as locality or company name, where wells are involved. A cursory review of the complaints indicated numerous complaints related to water quantity and water quality impacts to private domestic water supply wells. These problems were generally attributed by the complainant to poor practices by the operator (e.g., improperly cased wells). Other types of complaints included requests for baseline sampling before drilling began and dewatered well claims, as well as complaints related to produced water pits. Many of the complaints expressed concerns about methane gas contamination of wells. Most of the COGCC investigations of water quality concerns (including methane, sediment, and occasional salinity concerns) concluded that alleged well water impairments were not associated with CBM wells or CBM production activity. However, some occurrences of CBM contamination (methane gas contamination) of water wells have been confirmed as well as at least one instance where drilling fluid leaked from a pit, contaminating a nearby well.

Citizen complaints in Wyoming are processed by the Oil and Gas Conservation Commission (WOGCC), and complaints about both water quality and quantity have been received. The commission responds to all complaints, sends an inspector to the home or site associated with the complaint, interviews the complainant, and conducts a records check to determine if the water well has been permitted with the state, as required by state law. If the subject well is not permitted in Wyoming, the owner has no legal standing regarding potential impacts to the nonpermitted well water supply. The WOGCC requests assistance from the Wyoming DEQ or the State Engineer's Office (SEO), as appropriate, to investigate serious claims. Complaints exist only as paper records and are not available electronically. In Wyoming, complaints are often settled directly with the CBM companies, based on advance legal agreements between both parties, thus obviating state involvement.[17] The Wyoming SEO advises CBM companies to collect baseline water level data before drilling

[15]Papers submitted at the meeting are available through the National Academies Public Access Records Office. See Appendix C for the March 2009 meeting agenda.

[16]See cogcc.state.co.us/ (accessed April 7, 2010).

[17]J. Nelson, WOGCC, personal communication, April 2009.

new wells, to protect themselves and nearby well owners. However, no legal requirement exists for collection of baseline water quality or water level data.[18]

One registered complaint from the Powder River Basin in Wyoming cited increased erosion from unmanaged CBM produced water discharge (see Figure 5.6). A sustained period of CBM produced water entering the headwaters of a seasonally ephemeral channel resulted in substantial channel scouring, bank erosion, and head cutting, with the eroded channel migrating progressively upgradient. In this particular case, the water entering the channel was the result of overflow discharges from an upslope-produced water impoundment. Through litigation the CBM operator responsible for the overflow and subsequent produced water management was ordered to bring impoundment overflows into control and to discontinue discharge to the ephemeral channel.

In another documented case in Wyoming, a private citizen's complaint was filed against the state and a private CBM operator over CBM water discharges that were permitted and regulated. The private landowner charged that CBM waters released into ephemeral channels upstream from his property were altering portions of the land and preventing irrigation of hay meadows.[19] The state and the CBM operator were charged with violating the Clean Water Act and the Wyoming Environmental Quality Act.

Other citizen complaints have reached the courtroom. As of 2007, at least 20 farmers and ranchers in Wyoming, Montana, and Colorado had sued CBM operators and state agencies for damages related to CBM water discharges (McGuire, 2007). In 2003 a district court in Wyoming ruled that CBM operations had damaged nearby land used for cattle grazing. The plaintiffs testified that the CBM crews drove across the rangeland, mixed topsoil with salt-laden subsoil, and let hillsides erode away.[20] Landowners have also filed suit against permitting agencies and permitting procedures in some cases where the landowners have indicated adverse impacts on their land from produced water discharges. For example, in 2010 ranch owners in Wyoming contested before the Wyoming Environmental Quality Council (EQC) the terms of a discharge permit and the consequence of produced water discharges to private property under the terms of a Wyoming DEQ-issued discharge permit held by a nearby private CBM operator. The landowners claimed they lost productivity of agricultural land and trees due to salt buildup from CBM waters flowing across their Powder River Basin property. The Wyoming EQC sided with the plaintiffs. This complaint was presented before the Wyoming EQC following an EPA and private consultant finding of fault with the scientific basis of permitting being used by Wyoming DEQ.[21] The state of

[18]J. Harju, Wyoming SEO, personal communication, April 2009.

[19]See billingsgazette.com/news/state-and-regional/wyoming/article_5906e25d-058e-56fc-8b49-17ee4b5e012e.html (accessed April 29, 2010).

[20]See billingsgazette.com/news/state-and-regional/wyoming/article_1b83a02c-c303-504c-8365-068c5952a02d.html (accessed May 27, 2010).

[21]See billingsgazette.com/news/state-and-regional/wyoming/article_5f8ece00-2e57-11df-854d-001cc4c002e0.html (accessed April 29, 2010).

FIGURE 5.6 Stream bank erosion caused by headwater flows in ephemeral drainage of Barber Creek, Wyoming; water sourced from upgradient CBM storage impoundment releases, Powder River Basin. SOURCE: Used with permission from Gregory Wilkerson, Southern Illinois University Carbondale.

Wyoming ruled that the permit, which had been issued using rules since criticized by the EPA and state consultants, was no longer valid.

CHAPTER SUMMARY

Concerns about environmental effects associated with CBM production and produced water management are related to short- and long-term consequences associated with two general activities: (1) groundwater withdrawal associated with CBM extraction and (2) the disposal, management, and permitted discharge of produced water. Much of the information on effects derives from the Powder River Basin of Wyoming, where over 90 percent of CBM produced waters are discharged to the land or surface water or are applied as irrigation water to soils.

Groundwater

The potential effects on groundwater quality and quantity are related to groundwater withdrawals and infiltration from surface disposal impoundments that store CBM produced water. The extent of groundwater drawdown depends on the density of wells, the rate of pumping water from the coalbed by CBM operators, and the length of time that pumping has been ongoing. The time for the CBM-bearing aquifer to return to its original water pressure or level is a function of the extent of drawdown; site-specific aquifer characteristics such as porosity, permeability, and depth to the coalbed aquifer; climatic and hydrogeological conditions; and proximity and connectivity to recharge sources. Due to the distance between the deep coalbeds and the shallow groundwater aquifers and to aquifer compartmentalization, CBM extraction in the San Juan, Raton, Uinta, and Piceance basins is unlikely to cause lowering of the water table in shallow alluvial aquifers. However, research in the Powder River Basin, which has relatively shallower coal seams, has shown that hydrostatic heads in the coalbeds have been lowered between 20 and 625 feet in CBM production areas. Estimated recovery of groundwater levels in areas of the Powder River Basin where CBM production has ceased in recent years varies from 65 percent in the center of the area near the locus of the CBM wells to 87 percent near the edge of the basin over 10 years. This drawdown has been measured only in the coalbeds from which CBM has been extracted and which are not necessarily the same as groundwater aquifers used extensively as water supplies. An important characteristic that has not yet been thoroughly substantiated is the degree of local hydraulic connection between coalbed aquifers from which CBM and water are withdrawn and other aquifers in the Powder River Basin. Although an EPA study found no conclusive evidence of drinking water contamination by hydraulic fracturing fluid injection associated with CBM wells in a 2004 study (see Box 2.1), lack of comprehensive datasets and studies, and continued development of domestic oil and gas fields, including CBM, since the release of that study have continued to focus attention on hydraulic fracturing. The EPA is conducting a broader analysis of the potential effects on groundwater quality and public health from hydraulic fracturing throughout the entire oil and gas industry.

A primary mode for disposal of CBM produced water, especially in the Powder River Basin of Wyoming and somewhat in the Colorado portion of the Raton Basin, is in surface impoundments. Infiltration and percolation of impounded water can dissolve and mobilize preexisting salts or naturally occurring constituents such as sulfate, selenium, arsenic, manganese, barium, chloride, nitrate and soil solution TDS below impoundments. Studies in

Wyoming indicated no apparent change in groundwater quality as a result of interaction with underlying shallow alluvial groundwater for a substantial majority of impoundments studied; an increase in TDS, selenium, and sulfate in groundwater beneath some impoundment facilities; and improved water quality beneath a small fraction of impoundments. A monitoring well network and a monitoring program are integral parts of CBM produced water management plans that include disposal in surface impoundments.

Surface Water

The potential effects of CBM production and produced water discharge to surface water include water quality effects to perennial and ephemeral drainages and stream depletion from dewatering of coalbed aquifers. Studies that have been conducted on the effects of CBM produced water discharge on perennial stream water quality have produced equivocal results. Background (historical) data prior to CBM development are limited, making assessing the influence of climatic influences on in-stream flows difficult. Specific conductance and SAR of water resources may not be the most meaningful diagnostic or representative measures of CBM produced water influence on receiving water bodies, particularly in the Powder River Basin. Isotope analyses may provide more representative characterization of the influence of CBM produced water on groundwater and surface water.

Carbon isotopic "fingerprinting" studies have distinguished the presence of CBM produced water in the Powder River near areas of CBM production. These carbon isotope fingerprints become less evident as downstream flows are influenced by tributaries that are not themselves influenced by CBM produced water discharges. Use of isotope ratios or other isotope signatures of CBM produced water presence and effects may be useful to monitor and assess the presence and effects of CBM produced water on surface water and groundwater resources.

The committee was unable to find any published data or reports documenting measurable stream depletions due to CBM water production in the basins studied. The reliability of results from stream depletion modeling studies for the Piceance, Raton, and Northern San Juan basins in Colorado has not yet been evaluated against actual stream measurements in areas of CBM production. Similarly, the general assumption of "tributary" groundwater as a primary model input does not comport with the data available from the San Juan Basin.

Soil Quality and Agricultural Production

Several site-specific research studies and natural resource inventories have documented that application of CBM produced water to some soils in of the Powder River Basin has altered plant ecology and resulted in adverse soil with ecological, chemical, and hydrological consequences. The conclusions of these studies have not been extrapolated to wider geographic areas or watershed scales. The CBM produced water sourced from the Powder River Basin generally has lower TDS and constituent concentrations than that of the other western basins, and its utility for irrigation as a sole-source water supply is questionable under many conditions in the basin. Thus, CBM water sourced from other basins would have even less suitability for irrigation.

In cases where CBM produced water is used for irrigation, the practice will likely require intensive management, including selection of crops irrigated, timing and amount of produced water that is applied, and use of soil amendments. After use of CBM produced water ceases, additional soil management, including soil amendments, may be required to restore agricultural resources and impoundment sites to predevelopment crop production conditions.

Ecological Effects

Laboratory studies indicate that exposure to elevated concentrations of one or more of the chemical constituents TDS, bicarbonate, and other ions such as potassium and chloride can be toxic to some freshwater organisms. Most laboratory comparisons are based on mean concentrations and discharges of CBM produced waters and on direct and prolonged exposure of conventional laboratory test species to undiluted, untreated CBM produced water or its constituents. In the field, permitted discharges of CBM produced water often require treatment and a defined mixing zone (mixing between CBM produced water and receiving water) at the site of discharge. Testing these laboratory results against field studies and with species relevant to the study areas in the Powder River Basin has not yet been completed and would be a valuable contribution to determine the potential effects of CBM produced water on organisms.

Mean concentrations of sodium bicarbonate in many CBM produced waters are in the range of or exceed acute toxicity concentrations for some aquatic species tested in the laboratory. In situ (field) tests conducted in the Tongue and Powder rivers showed mortality to some species when levels of bicarbonate exceeded laboratory toxicity threshold concentrations for test species. However, these results were the result of direct exposure to undiluted CBM produced water, a situation that would be unlikely in perennial waters where fish are found because of permitted discharge requirements.

Most information on sensitivity of aquatic organisms to dissolved ions has been derived from short-term laboratory toxicity tests. While laboratory approaches may provide an approximation of potential effects, toxicity tests are limited in their ability to predict effects on natural populations and communities in the field. To date, few field assessments have investigated the effects of CBM produced water discharges on aquatic communities, partly due to the difficulties in conducting robust experiments that account for interacting habitats, natural and human-induced differences in water quality, background (pre-CBM development) conditions, limited lengths of time to complete studies involving community transitions, and species migration. Two field studies conducted to date noted difficulty in identifying any direct effects of CBM discharges on fish assemblages in large-volume perennial flowing rivers (the Powder and Tongue rivers). A comprehensive assessment is currently being conducted to establish current conditions for habitat and aquatic communities for the Powder River Basin in order to measure and monitor future changes.

The potential adverse effects of CBM discharge to ephemeral streams and riparian systems are changes in the timing and amount of streamflow, increased stream bank erosion and instability, increased suspended sediment concentrations and turbidity and downstream sediment deposition, changes in riparian plant communities, and increased stream water and sediment salinity. Effects to algae, aquatic invertebrates, fish, amphibians, and other biological aspects of streams and rivers as a consequence of these discharges have not yet been rigorously documented. One study found greater percentages of nonnative plant species in channels receiving produced water than in those that did not receive CBM produced water.

Citizen Complaints

Although the committee was not able to find published evidence of any widespread effects of dynamic alteration in ephemeral stream channels due to regulated and managed CBM produced water discharges, increased erosion from unregulated and/or unmanaged CBM produced water discharge has been reported. Several cases are also documented in which private landowners brought their complaints against CBM operators and state authorities to court over permitted and regulated discharges to ephemeral channels and to the surface of private lands. Citizen complaints related to CBM activities that are cataloged and investigated by several states with CBM production, comprise primarily concerns about water quantity and quality impacts to private domestic water supply wells.

Baseline information on flows was generally not available for complaints related to ephemeral drainages. For drainages already receiving CBM discharges, hydrological and geochemical characteristics of flows in nearby drainages could be used as surrogate baseline conditions. Similarly, the Wyoming SEO advises CBM companies to collect baseline water level data before drilling new wells, to protect themselves and nearby well owners. However, no legal requirement exists for collection of baseline water quality or water level data.

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CHAPTER SIX

Technologies and Costs for Coalbed Methane Produced Water Treatment

Numerous treatment technologies may be used for coalbed methane (CBM) produced water to achieve water qualities suitable for beneficial uses or to comply with permitted discharge requirements. The vast majority of CBM produced water treatment is completed for the purpose of disposal (see Chapters 4 and 5). Treatment is therefore generally performed either as a regulatory requirement of the Underground Injection Control (UIC) program to facilitate subsurface drip irrigation or for National Pollutant Discharge Elimination System (NPDES)-issued permits for discharge to ephemeral and perennial drainages (see Chapter 3). If the water is treated prior to deep reinjection disposal the treatment is done for operational purposes or to address bacterial contamination (see Chapter 4).

The selection of CBM water treatment options varies as a function of several factors, including (1) produced water quantity and quality; (2) allowable quality of discharged water; (3) the water treatment technique or techniques that can be or are used; (4) transportation and/or storage needs for produced water prior to and after treatment, until disposal or use; and (5) the regulatory framework in place, including water rights and transfer, and allowable uses for treated water. These factors and the resulting effects on costs of treatment contribute to variation in the predominant water treatment (and management) strategies used throughout the western CBM basins. For example, within the Powder River Basin, relatively low salinity and other dissolved constituent concentrations, high water production rates, and perennial shortages of water have led to increased interest in the possibilities of treating the water for beneficial uses rather than disposal (see Chapters 2 and 4). However, most CBM produced water in the Powder River Basin is presently treated only for compliance with NPDES permit requirements for surface discharge. The same permitting and technological treatment issues apply to other western CBM basins, which have employed surface discharge for CBM produced water in a very limited way. Within the San Juan, Raton, Uinta, and Piceance basins, treatment of waters with high total dissolved solids (TDS) and high-salinity is limited primarily to operational purposes for disposal by deep-well reinjection, the primary CBM produced water management method employed in these basins. These variations in treatment and disposal options occur despite the fact that currently available water treatment technologies allow almost any water quality requirement or goal to be achieved, regardless of the initial quality or quantity of the source water, although at varying costs.[1] The Clean Water Act expresses the necessary level of treatment for discharges to be that achievable with the best available technology at an economically achievable level.

This chapter includes information specific to the treatment techniques predominantly used today for CBM produced water in the western CBM basins, as well as some of the techniques for which significant field-scale tests have been conducted but that are not necessarily currently used on a commercial scale. Costs of these primary treatment technologies are also discussed.

Comprehensive, independent, objective evaluations of water treatment techniques for CBM produced water, their effectiveness, and costs have not been widely available, nor are they easy to conduct because of issues of vendor confidentiality and the many variables to consider in treating produced water in different locations. A broad, independent technical assessment of treatment technologies potentially applicable to CBM produced water, including those used for pre- and posttreatment, desalination, and waste disposal, is currently being conducted as part of a collaborative research project led by researchers at the Colorado School of Mines. The project has released the first edition of its technology assessment in which 54 water treatment technologies and disposal methods were addressed (RPSEA, 2009). The document has served as a source of independent information for the primary CBM produced water treatment techniques discussed in this chapter. The committee also collected information from other published sources as well as from water treatment vendors in the western states.

PRIMARY TREATMENT TECHNOLOGIES FOR CBM PRODUCED WATER

A single water treatment technology is generally optimized to address specific constituents in the water but is not usually effective in treating every potential constituent. Thus, depending on the initial quality of the produced water, its eventual use (or disposal), and desired constituent concentrations, one technique alone may serve the primary treatment purpose, or several treatment techniques may be used in sequence to achieve a desired water quality. Sodium adsorption ratio (SAR, a numeric expression of the concentration of sodium, relative to the concentration of calcium and magnesium in produced water; see also Chapter 2) and salinity (measured as electrical conductivity [EC]) are the constituents of

[1] J. Veil, Argonne National Laboratory, personal communication, May 20, 2009; also D. Stewart, Stewart Environmental Consultants, Inc., presentation to the committee, March 30, 2009.

CBM produced water that usually receive the most focus, although treatment for additional constituents, including fluoride, barium, ammonia, bicarbonate, and some trace elements, may be necessary to meet NPDES, UIC, state, and/or tribal regulatory requirements for surface discharge or subsurface reinjection. Some amount of pretreatment may be required as a compliment to treatment for SAR and EC or for disposal by subsurface drip or deep-well reinjection; pretreatment techniques may include degassing, settling, filtration, coagulation, flotation, and/or flocculation. These techniques are not discussed further.

Table 6.1 presents the more commonly occurring constituents in CBM produced water and the treatment technologies that are able to effectively remove or substantially reduce the concentration of these constituents: (1) ion exchange; (2) reverse osmosis; and (3) Freeze/Thaw Evaporation (FTE). The table also includes adsorption by cation exchange using zeolites and phytoremediation techniques although these techniques are not in common use for treating CBM produced water at this time. Although organics and biological agents are not known to be present in CBM produced water to any significant degree, they are included in the table for purposes of comparison between technologies. Table 6.2 provides a summary of the principles of operation, advantages, disadvantages, limitations, and relative costs of these treatment systems for CBM produced water. Each of the treatment techniques is then reviewed in detail.

Ion Exchange

Ion exchange treatments have been developed specifically in response to the need to reduce the SAR in the sodium concentration of produced water. Ion exchange systems function by capturing and removing a specific ion type within the CBM produced water. The specific purpose of ion exchange is to remove sodium by replacement with a different cation. By this fact alone, SAR will be reduced. Ion exchange resins capture specific dissolved ions and release other (like-charged) ions. Thus, the concentration of a specific ion of concern (e.g., sodium in agricultural areas) can be substantially reduced. The adsorption characteristics and saturation configuration of an ion exchange resin are specific to the ion targeted and a function of the resin composition. In as much as the fixed- and fluid-bed resin exchange technologies that are being used employ primarily sodium cation-specific resins, these treatment systems do not remove substantial proportions of anions or other cations in the produced water stream.

Exterran Water Management Services has developed ion exchange water treatment technologies that use a modification of a Higgins Loop CCIX technology—a patented process exclusively licensed from Severn Trent Services—referred to as continuous countercurrent ion exchange systems for removing sodium and other cations from produced water. Higgins Loop is the most widely used ion exchange technology for CBM produced water treatment (RPSEA, 2009). Approximately 18 percent of all permitted discharge

TABLE 6.1 Estimated Treatment Technology Effectiveness for Constituent Types in CBM Produced Water

	Produced Water Constituents—Effectiveness of Removal by Indicated Treatment Expressed as percentages									
Treatment Method	TDS	Specific Conductance	SAR—sodium	Bicarbonate	Barium	Fluoride	Ammonia	Trace elements	Organics	Biological Agents
Ion exchange	Effective	Effective	Very effective	Very effective	Very effective	Very effective	Very effective	Variable	NA	NA
Reverse osmosis (RO)	Very effective	Very effective	Very effective	Very effective	Very effective	Very effective	Very effective	Very effective	Very effective	Very effective
Freeze/Thaw Evaporation (FTE)	Very effective	Very effective	Very effective	Very effective	Very effective	Very effective	Very effective	Very effective	Very effective	NA
Zeolites	Effective	Effective	Effective	Ancillary	Ancillary	Ancillary	Very effective	Very effective	Very effective	NA
Phytoremediation	NA	NA	NA	NA	NA	NA	Very effective	Very effective	NA	NA

NOTE: "Very effective" indicates data from one or more studies showing ≥70 percent removal of the given constituent; "Effective" indicates data from one or more studies showing some and up to 70 percent removal of the given constituent; "NA" indicates not applicable because the method is not optimized for that constituent; "Variable" indicates situation-specific approaches and lack of data to make a determination; "Ancillary" indicates that, although this is not the primary target for the treatment method, the method has proven effective at significantly reducing the constituent concentration. More definitive or precise evaluations of the effectiveness of these methods for applications to CBM produced water were not possible because of the lack of independently acquired and verified data, different pretreatment applications, and different starting produced water qualities in different studies. "Organics" is a nonspecific term and the types of organic constituents treated by a given method may not be the same as those treated with another method.

SOURCES: ALL Consulting (2003, 2005), IOGCC and ALL Consulting (2006), and RPSEA (2009). Other sources used to create this table are cited in the main text corresponding to each treatment method in this chapter.

TABLE 6.2 Advantages and Disadvantages of Common CBM Produced Water Treatment Methods

Treatment Method	Use	Principle	Advantages	Disadvantages	Limitations	Relative Cost
Ion exchange	Extensive use in Powder River Basin; limited trial use in other basins	Selective removal and replacement of sodium using cation exchange resin; ancillary treatment is bicarbonate—TDS reduction; can be combined with secondary treatments for fluoride, barium, ammonia, SAR reduction	Very efficient specifically for sodium (SAR) reduction; extensive history; low energy requirement; capable of processing large volumes of water; proven technology; all-weather operational; long operating life; operation time of 99% in service; waste stream can be eliminated with marketable dried product or reduced to 5 percent of input volume; certain systems are portable and mobile	Requires large volumes of water to be cost effective; elimination of concentrated brine waste stream may be required; turnkey operation involving hazardous material; requires routine, regular maintenance; resin needs periodic replacement; constituent removal is specific to resin; treatment process specifically targets sodium; can be combined in series for removal or reduction of other constituents	Significant infrastructure; involves hazardous material handling	High initial capital investment cost; relatively low per-unit treatment cost once in operation

continued

TABLE 6.2 Continued

Treatment Method	Use	Principle	Advantages	Disadvantages	Limitations	Relative Cost
Reverse osmosis	Specialized use in San Juan, Raton, Uinta, and Piceance basins; trial use in Powder River Basin	Pressurized filtration through fine-pore membrane	Highly effective, can remove most contaminants; can minimize waste stream for disposal; proven technique and technology	Requires frequent maintenance; produces concentrated brine waste stream; treated water quality may exceed needs; substantial energy requirement; may require membrane replacement; turnkey operation; requires large volumes to be cost effective	May require pretreatment; temperature sensitive—operates in 50 to 95° F range; significant infrastructure, relatively immobile	High initial capital investment cost; high per-unit treatment cost; waste stream disposal cost
Freeze-Thaw Evaporation	Application specific to limited locations; initially developed for conventional oil and gas waste handling	Distillation by freezing and evaporation	No energy input required at treatment facility; environmentally benign process; no hazardous waste material handling; relatively inexpensive per-unit treatment cost	No mobility of treatment facility; often requires hauling water long distances; requires large, dedicated land area; only effective in subfreezing environments, for limited time periods; requires full-time onsite management when in operation	Wastewater storage ponds and basins may be hazardous to waterfowl; may require canopy screening; requires access to disposal facility for concentrate; unpredictable process timing	High initial capital cost for land acquisition and basin construction; relatively high per-unit treatment cost

Zeolites	No evidence of large-scale commercial use; primarily used on experimental or trial basis	Selective removal and/or replacement of sodium using cation exchange aluminosilicates (naturally occurring mineral deposits)	Utilizes naturally occurring mineral adsorbent; no hazardous waste material handling; minimal capital investment; suitable zeolite deposits occur within Powder River Basin; concept well known	Zeolites require initial conditioning to remove sodium; flushing and periodic replacement required; produces waste stream; multiple engineered water treatment steps involved; requires large operational footprint and extensive water storage and handling	Technology has not been tested on water qualities found in San Juan, Raton, Uinta, and Piceance basins; questionable effectiveness with saline-brackish waters; efficiency of sodium removal limited by specificity of zeolite	Minimal capital and equipment costs; low per-unit treatment cost (if zeolites are ever applied at larger scale, they may incur high initial capital costs, similar to ion exchange)
Phyto-remediation	Extensive wetlands have evolved in Wyoming due to discharges and seeps; limited direct or intentional construction or use	Consumptive water use and selective removal of elements by plants	Utilizes natural and constructed wetlands as water treatment mechanism; no energy input required; no hazardous waste material handling; no waste stream; environmentally benign; enhanced wildlife/waterfowl habitat	Limited or no effectiveness for salt or sodium removal; potential evapoconcentration of salts; consumes water; requires large operational footprint; has potential to enhance invasive plant species and ecological community change; nonsustainable in absence of water; may require periodic flushing	No net long-term beneficial water treatment in context of CBM produced water treatment; functional benefits may be temporally limited	Ranges from none to extensive if wetlands or plant community construction required; only per-unit treatment cost is water delivery

NOTE: Unless stated, technologies summarized in table do not provide treatment or control for bacteria.

water in the Wyoming portion of the Powder River Basin is currently being treated with this technology.[2] Water to be treated is passed through a large bed of molecularly adsorbent resin beads. Sodium and, secondarily, other positively charged molecules such as potassium, calcium, and magnesium are adsorbed onto the resin. Collateral treatment includes degassing bicarbonate and reducing alkalinity of the treatment water (see Figure 6.1). Additional unit configurations can be included to address issues of fluoride, ammonia, barium, heavy metals, radium, nitrates, arsenic, and uranium.[3]

This process can lower SAR values by up to 98 percent and substantially lower the TDS and bicarbonate concentrations of produced water while producing a concentrated brine waste stream, although the method may not treat TDS to the level necessary to meet NPDES discharge regulations; posttreatment may be needed to achieve those standards (RPSEA, 2009). Currently available commercial operations being used in the Powder River Basin have water treatment capacities of as much as 35,000 barrels per day per unit.[4] The actual amount of sodium removal depends on the resin-to-water ratio, the produced water flow-through volumes and rates, and the frequency of resin reconditioning. Brines are generally disposed of by deep-well injection through the UIC program administered by the Environmental Protection Agency (EPA). The waste stream can be reduced typically to as little as 3 percent or less of the inflow stream.

The patented Drake system[5] is a variant of the ion exchange process that was developed specifically for treatment of sodium bicarbonate-rich CBM produced water of the Powder River Basin. The system uses a modified fluid-bed ion exchange treatment that produces low-sodium treated water and minimal sodium sulfate brine (1 to 3 percent of influent water). The brine can be reduced by drying and has a commercial value as sodium sulfate (Glauber's salt), a chemical salt used in the manufacture of detergents and paper. Drying reduces the brine stream volume by over 86 percent, from a liquid to a dried salt that is easily managed. Thus, no waste stream or product needs disposal. System treatment capacity is approximately 8,500 barrels per day. Although primarily designed for treating produced water with relatively low TDS, sodium removal (and SAR reduction) is reported to be highly effective. Although the footprint for the facility is greater (approximately 2 acres) than that for a Higgins Loop system, the energy requirements may be slightly lower (RPSEA, 2009).

A third commercial ion exchange process uses two or three compressed resin beds, instead of one; the multiple compressed beds are used to achieve simultaneous cation and anion removal. The Eco-Tec RecoPur system[6] is designed for reducing SAR and conductiv-

[2]T. Olson and D. Beagle, Exterran Water Management Services, personal communication, August 4, 2009.
[3]Ibid.
[4]Ibid.
[5]See drakewater.com/AboutUs.html (accessed March 5, 2010).
[6]See www.eco-tec.com/products/coal_bed_methane.php (accessed February 23, 2010).

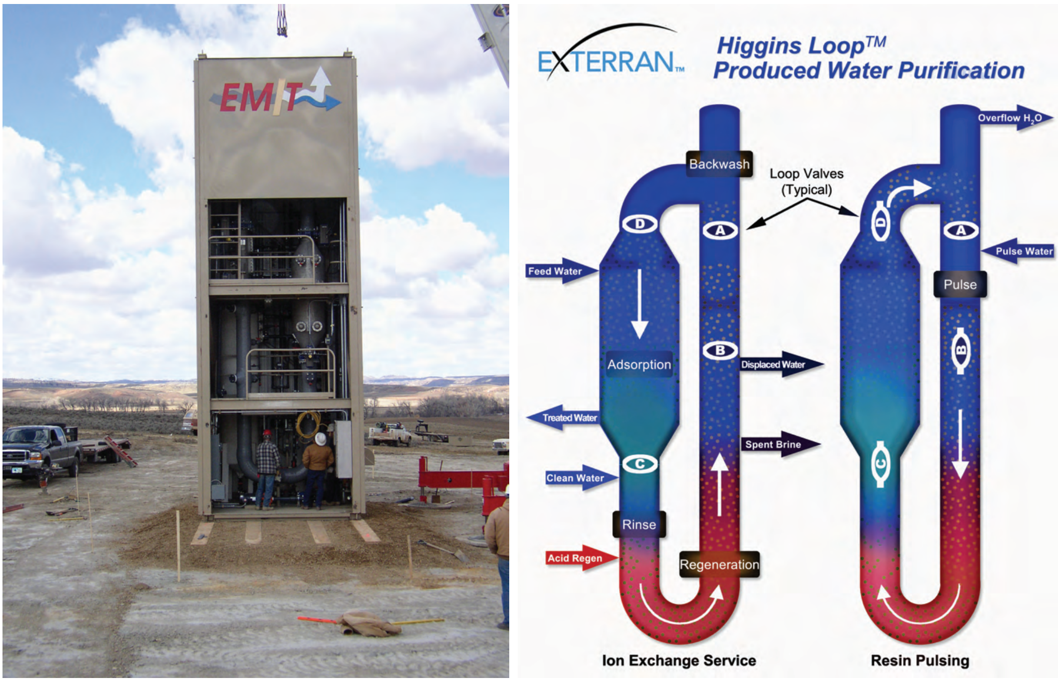

FIGURE 6.1 Left: Exterran Water Management Services facility in operation in the Powder River Basin shows the approximate footprint of the main treatment complex; the total footprint may be up to 450 square feet. Right: Diagrammatic illustration of the modified Higgins Loop process. The letters A, B, C and D represent main control valves that separate the four major vessels of the Higgins Loop. When closed they hold the resin, produced water and process fluids in place in the respective chambers. When opened they allow the resin to pulse, or move hydraulically, from chamber to chamber. In both of the pictures shown the A Valve is closed. The A Valve is closed during the 'Pulse' Cycle to contain the water used to move the resin. It opens temporarily during the Treatment/Regeneration Cycle while resin in the Backwash Vessel replenishes the supply in the Pulse Vessel.
SOURCE: Used with permission from Exterran Energy Solutions L.P. (Parent company of Exterran Water Management Services LLC).

ity values and reports a high water processing capacity (up to 36,000 barrels per day). The system is designed to have a smaller operational footprint than other ion exchange methods but has, to date, been used only in pilot-scale (trial basis) CBM operations in the Powder River Basin (RPSEA, 2009).

Reverse Osmosis

Reverse osmosis (RO) is essentially a pressurized mechanical filtration process. Filtration occurs by forcing water under pressure to pass through a semi-permeable membrane.

Impurities within the source water are retained on the pressurized side of the membrane, and (nearly) pure water passes through the membrane to the other side. RO can remove salts, particulate matter, microorganisms, and organic and inorganic chemicals, depending on the membrane characteristics. Some pesticides and low-molecular-weight organics can pass through RO membranes (NRC, 2008).

The RO process can remove 95 to 99 percent of any sodium, magnesium, calcium, barium, silica, sulfates, chlorides, nitrates, and total organic carbon (TOC) in CBM production water, resulting in reduction of TDS, SAR, and constituents responsible for hardness and alkalinity (Bergsrud et al., 1992).[7] RO is commonly used for brackish water and seawater desalination in many locations where potable water supplies are limited.

RO treatment requires substantial energy input, and energy requirements increase with the salinity of the water and reduction in membrane pore size. Fouling of the membrane (caused by chemical precipitation on the membrane) occurs routinely, and pretreatment of the inflow water is often necessary to minimize fouling and to extend membrane life (IOGCC and ALL Consulting, 2006). Depending on the initial quality of the water, pretreatment can include clarification, filtration, ultrafiltration, pH adjustment, chlorination for bacterial control, and removal of free chlorine. RO is operational only above freezing temperatures, and membranes perform most efficiently between 50 and 90° F (ALL Consulting, 2003).

RO units require regular maintenance, and membranes periodically need to be replaced. In addition, the feed stream (water being treated) becomes increasingly concentrated as treatment proceeds and clean water is produced. This consequence necessitates routine, periodic cleaning of the membrane and disposal of the waste concentrate. The most frequently used method of waste concentrate management is deep-well injection/disposal to UIC-permitted Class II wells.

A number of pilot and full-scale RO systems are in operation in the western CBM basins. For example, an RO facility in the Powder River Basin has a treatment capacity of 72,000 barrels per day (3 million gallons per day) to meet all discharge requirements to an ephemeral stream in Wyoming. This particular facility consists of a multimedia inlet filtration unit (to remove particulate material), a packed-bed ion exchange softening system, a primary RO system, and a brine-recovery RO system. The system recovers 96 percent of the water, and the remaining water is sent to onsite evaporation ponds (Welch, 2009).

Freeze Separation Process

One method of produced water treatment that has been used successfully for conventional oil and gas produced water management at commercial scales is the freeze separation

[7]See also www.excelwater.com/eng/b2c/rejection.php (accessed February 23, 2010).

process, which takes advantage of the fact that water containing dissolved salts freezes at a lower temperature compared to the freezing point of pure water (32° F). Partial freezing of produced water, which contains dissolved salts, begins when the water is cooled below 32° F. The initial ice crystals that form comprise relatively pure water (lower salt concentration) relative to the concentration of the remaining unfrozen solution (essentially a brine). Continued formation of ice crystals will gradually concentrate dissolved solids and other constituents in the brine which can then be drained.

The Freeze/Thaw Evaporation (FTE) process is a variation on freeze separation in which produced water is stored in a holding pond until the air temperature drops slightly below freezing and the water is then pumped to a freezing pad on which relatively pure ice crystals are collected and the remaining brine is drained. The pure ice crystals can be thawed, providing a source of high-quality water; alternatively, the ice can be evaporated as relatively salt-free water. This process can be repeated until the progressively more concentrated brine is of a manageable volume (see Figure 6.2). The volume of salt-rich water is much smaller than the initial volume of produced water and can be disposed of or discharged where permitted (RPSEA, 2009).[8]

FTE is only effective in environments that reach seasonal subfreezing temperatures for a substantial number of days, and the system requires several tens of acres of dedicated land area. Careful management is essential during critical freezing and thawing time periods, since the concentrated brine solution itself requires disposal or treatment (RPSEA, 2009).[9]

FTE has been used successfully to manage produced water from conventional oil and gas fields in Wyoming and New Mexico at commercial scales (RPSEA, 2009). Both freeze separation and FTE have been advanced in field-scale demonstrations for CBM produced water in Alaska, Canada, Wyoming, Colorado, and the San Juan Basin in New Mexico (Triolo et al., 2000; ALL Consulting, 2003).[10]

Zeolites

Researchers have investigated the potential for use of naturally occurring processes and minerals to remove sodium and other dissolved constituents from CBM produced water. Zeolites are naturally occurring alumino-silicates (minerals) with relatively high surficial adsorption capacity. Chemically, zeolites are similar to clay minerals, although they are classified as adsorbents. Natural zeolites occur in distinct geological environments, including volcanic tuffs that have been altered by saltwater and alkaline water. Similar to the case of synthetic resins used in ion exchange systems, dissolved substances in water accumulate on

[8]J. Boysen, BC Technologies, Inc., presentation to the committee, March 30, 2009.
[9]Ibid.
[10]Ibid.

FIGURE 6.2 Seasonal cycle for freezing, thawing, and evaporation of produced water in Wamsutter, Wyoming. Top: Summer evaporation of melted, relatively pure ice. Bottom: Winter freezing of produced water solution to result in relatively pure water in the form of ice crystals. SOURCE: Used with permission from John Boysen, BC Technologies, Ltd.

zeolites and zeolite adsorption surfaces need to be regenerated (cleaned) to remove the accumulated substances. Although research has been conducted regarding the use of zeolites in the treatment of CBM produced water (see descriptions below), no commercial-scale zeolite water treatment operations for CBM water treatment are known at this time.

Studies by Zhao et al. (2008, 2009) have shown that treatment of CBM produced water from the Powder River Basin with calcium-enriched zeolites reduced SAR and electrical conductivity (or EC, a surrogate for salt concentration) values to levels compliant with permitted discharges to surface waters within the Powder River Basin. This treatment was also reported at a reduced cost compared to reverse osmosis. The process involved using a naturally occurring sodium-rich zeolite to alternately soften water, initially exchanging sodium from the zeolite for calcium within the treatment water, resulting in a calcium-rich zeolite. Sodium-rich CBM produced water was then introduced into the calcium-rich zeolite, resulting in a reversed process of sodium removal, thereby reducing the SAR of the outflow water.

A study of a similar nature was completed by Huang and Natrajan (2006), using the St. Cloud zeolite, which occurs naturally in New Mexico. They determined that this particular zeolite has a low selectivity of sodium over calcium. In their case, the low selectivity of the zeolite for sodium resulted in significant limitations with regard to the effectiveness of this particular zeolite for treatment of CBM water sourced from the San Juan or Raton basins.

Phytoremediation—Wetlands

Phytoremediation (a category of bioremediation) is the treatment of contaminated soil or water by growing plants, which reduces the need to treat or excavate the contaminated material and dispose of it elsewhere.[11] The use of plants for contaminant mitigation is founded on the premise that plants can degrade organic pollutants or stabilize some contaminants (primarily nutrients) by acting as accumulators, filters, traps, or agents for sequestration. When such an approach encompasses the role of soil and microbes as well, the process is referred to as bioremediation (Bauder, 2008).

Typically, phytoremediation has involved the use of constructed or natural wetlands, with the focus principally on dealing with sediment, plant nutrients, or bacteria. Natural wetlands essentially filter water through the accumulation of carbon in organic matter, the accumulation of nitrogen and phosphorus, and the trapping of suspended matter and some pathogenic elements. However, neither natural nor artificial wetlands with flow-through

[11] See toxics.usgs.gov/definitions/phytoremediation.html (accessed February 23, 2010).

water have any significant capacity for removal of salts or sodium.[12] Studies prompted by recent CBM industry expansion have investigated, without significant field-scale success, potential uses of agricultural plants for the uptake and removal of salt—primarily sodium—from CBM produced water applied to agricultural landscapes (Bauder, 2008). However, similar to application of zeolites, no commercial-scale operations for CBM water treatment using phytoremediation are known at this time.

Research with an artificial sedge wetlands system to treat CBM produced water has investigated constituents concentrated in produced water, mainly SAR, iron, and barium, and whether these constituents could be treated cost effectively with artificial wetlands. The constructed wetlands effectively sequestered iron and possibly barium but resulted in no significant capability for reducing salinity or SAR (Schulz and Peall, 2001). Barnes et al. (2002) found that wetlands of the Mkuze Wetland System in northern KwaZulu-Natal served as a sink for significant amounts of calcium, potassium, and silicon but served a lesser role in the sequestration of magnesium and sodium. These results were consistent with a study of wetlands treatment of Powder River Basin water, reporting preferential uptake of calcium and magnesium, relative to sodium uptake by wetlands plants. As a result, SAR of shallow alluvial groundwater actually increased over time (Bauder et al., 2008).

A similar study performed at Clark County Wetlands Park, Nevada, reported that the natural wetlands filtering process did not affect salinity, dissolved oxygen, chloride concentrations, alkalinity, hardness, turbidity, or total suspended sediment. Moderate reductions to pH, sulfate, and nitrate were observed, but the reductions were considered negligible (Pollard et al., 2002). Lymbery et al. (2006) reported that *Juncus kraussii* (cattails), in constructed wetlands sites effectively removed nitrogen and phosphorus (plant nutrients) but had essentially no net effect on sodium removal.

Ancillary, Secondary, and "Polishing" Treatments

Although sodium and salinity are the principal constituents of CBM produced water that have received the most attention with respect to treatment, NPDES and state and tribal regulatory agency permits may require treatment for other constituents prior to discharge of CBM produced water to surface waters. These other treatments are generally either a specific requirement for disposal (i.e., filtration, chlorination, pH adjustment, bacterial and viral control) or specific to unique constituents that are found within the produced water and require treatment for a specific water use. In addition, the Safe Drinking Water Act requires EPA to protect potential underground sources of drinking water from contamination that could occur from subsurface injection. This statute has also been applied to shallow wells

[12] See www.netl.doe.gov/technologies/oil-gas/Petroleum/projects/Environmental/Produced_Water/15166.htm or cfpub.epa.gov/ncer_abstracts/INDEX.cfm/fuseaction/display.abstractDetail/abstract/8742/report/F (accessed February 23, 2010).

used to discharge CBM produced water through alluvial aquifer recharge and to the use of horizontal subsurface drip discharge.

Constituents that have instigated additional or ancillary treatment include fluoride, barium, ammonia, and bicarbonate (Rice and Nuccio, 2000; Wyoming DEQ, 2000; Veil, 2002).[13] To date, no substantial evidence of entric bacterial or pathological contamination presence has been documented in CBM produced water.

Ancillary treatments that deserve mention include chlorination and nanofiltration of coal fines (particulate matter) prior to reverse osmosis treatment. At present, no evidence exists of substantial use of any of these treatments on a large commercial scale for the treatment of CBM produced water, either for beneficial use or disposal.

TREATMENT AND DISPOSAL COSTS

Treatment and disposal costs are variable and are a function of numerous circumstances and conditions, including the extent of treatment required, access to disposal facilities, water production volumes, water transport distances, and natural variations among basins. Variations in the price of natural gas may also play a role (see Chapter 2). Table 6.3 presents a summary of reported treatment and disposal costs for CBM produced water gathered from several sources, including reports, conference proceedings, news releases and industry fact sheets. Technologies which are not currently used at commercial scale have not been included in the table. Another factor affecting costs for treating CBM produced water is that produced water volumes will diminish through time (see also Chapter 2), with the implicit concern that the delivered water volume will not remain constant.

For the CBM producer, the most influential factor in CBM produced water management decision making is the cost for treatment plus associated infrastructure, which may include costs to gather, transport, deliver, treat, and/or discharge the produced water. Because of these variables, the committee was unable to find either complete or precise cost estimates to quantify water management costs more precisely than those presented in the table. The EPA study (Box 3.2) originally intended to survey CBM operators' produced water treatment practices and costs, as a basis for assessment of whether technology-based treatment and effluent limitation guidelines should be applied to CBM produced water. The RPSEA study is now compiling this kind of information and is working in partnership with EPA and other groups.

Ancillary costs may include the cost of transportation, pipelines, irrigation systems and management per unit area of land irrigated plus the cost of crop management, harvesting, storage and transportation. Regulatory requirements regarding how the produced water may be used (see also Chapters 3 and 4) further constrain the type of treatment facility

[13] See also www.patentstorm.us/patents/7081204/description.html (accessed February 23, 2010).

TABLE 6.3 Summary of Reported Produced Water Treatment and Disposal Costs

Disposal or Treatment Method	Unit Cost/ Barrel	Capital Equipment Cost or Access Fee	Reference
Deep-well injection	\$0.50–\$1.75	\$400,000 to \$3 million	Veil et al. (2004); ALL Consulting (2003)
	\$0.75–\$4.00		Huang and Natrajan (2006)
	\$3.00–\$5.00		Hightower (2003)
Fluid-bed resin exchange—Drake Water Technologies	\$0.12–\$0.30	\$325,000	See www.pttc.org/newsletter/3qtr2008/v14n3p12.htm (accessed February 23, 2010)
Fixed-bed resin exchange—Exterran EMIT Technology	\$0.15–\$0.60		See www.pttc.org/newsletter/3qtr2008/v14n3p12.htm (accessed February 23, 2010)
Subsurface drip irrigation	\$0.16–\$0.24	\$6,000/acre[a]	J. Zupancic, BeneTerra, Inc., LLC, personal communication, December 22, 2009
Freeze-Thaw Evaporation	\$0.24–\$0.32[b]; \$0.75–\$1.00	\$1.75 million to \$2 million	ALL Consulting (2003); J. Boysen, BC Technologies, Inc., presentation to the committee, March 30, 2009
Reverse osmosis	\$<0.01–\$0.10[c]	\$200,000 to over \$2 million	ALL Consulting (2003)
	\$0.01–\$0.03		Stewart and Takichi (2007)
Land-applied using soil amendments	\$0.06–\$0.45	Cost of water-spreading infrastructure/irrigation equipment; \$3,000–\$5,000 per acre-foot	Huang and Natrajan (2006); Zhao et al. (2009)

[a]Per-unit costs and capital equipment costs are mutually exclusive (i.e., one or the other).
[b]These two costs refer to the freeze-thaw operation and disposal of the concentrated effluent.
[c]Costs include other treatment techniques and waste stream is deep-well reinjected.

NOTE: The presentation of costs above does not take into account specific flow rates of CBM produced water from a typical well. Otton (2006) indicate that the range of flow for CBM wells is from 12-234 barrels per day per well (0.35-6 gpm) depending on CBM basin. A bathroom faucet in a home at 80 pounds per square inch gauge turned on most of the way will be close to the lower range and a water hose opened all the way is approximately the upper range. These are very small flows for wellhead treatment systems. Treatment equipment for these sizes is similar to point of entry, point of use, fish ponds, or swimming pool applications. Vendors for this size equipment are vastly different than for centralized systems with flows from 100 to 200 times greater. Only when a number of CBM produced water wells can be centralized would economies of scale be achieved for the water treatment vendor and the well operator with regard to treatment costs. However, the capital for the collection and transport of the untreated water from the well head to a centralized system may be higher that the capital for the treatment equipment.

that may be employed. Certain treatment technologies are optimized for large, long-term, and constant-water flow-throughs, which cannot be assured in the case of CBM produced water treatment. The single most-significant cost associated with treatment for discharge is disposal of waste brine. The second most-significant cost associated with treatment for discharge in the Powder River Basin is transportation associated with brine hauling and disposal.[14]

CHAPTER SUMMARY

Currently available water treatment technologies allow almost any water quality requirement or goal to be achieved, regardless of the initial quality or quantity of the source water. Mitigating factors such as costs, uncertainty about quantities and duration of water supply, water transport and storage, and the legal framework for application of produced water to beneficial uses place practical constraints on the flexibility to use these technologies to achieve a desired water quality for a specific purpose.

Treatment technologies with extensive performance histories have been demonstrated as effective and have been implemented on a commercial scale to achieve any regulatory discharge permitting requirements for CBM produced water, particularly in the Powder River Basin. Regulatory agency permitting requirements vary specifically with each permit. In nearly 100 percent of the cases where CBM produced water is being treated, the degree of treatment of CBM produced water is driven by regulatory requirements for disposal, permitted discharge, or waste management. In few instances is CBM produced water being treated for the primary or specified purpose of achieving quality for beneficial use.

Within the Powder River Basin, approximately 15 to 18 percent of the produced water is being treated to reduce sodium and salinity levels to meet NPDES-permitted SAR and EC discharge requirements. The predominant treatment (90 to 95 percent) is ion exchange for reduction of sodium and bicarbonate concentrations. Within most other basins, the predominant water management strategy is disposal by deep-well reinjection.

Capital construction costs and per-unit water treatment costs vary across information sources and treatment technologies. Per-unit treatment costs are set by a separate "treatment" industry and are a reflection of research and development costs, operation costs, and input and outflow water qualities and quantity. The single most significant cost associated with treatment for discharge is disposal of waste brine. The second most significant cost associated with treatment for discharge in the Powder River Basin is transportation associated with brine hauling and disposal. Even where CBM produced water is intentionally put to beneficial use, the cost of implementation of such use (e.g., the cost of transportation,

[14] D. Brown, BP America, presentation to the committee, June 2, 2009; also T. Olson and D. Beagle, Exterran Water Management Services, personal communication, August 4, 2009.

pipelines, irrigation systems, and management per unit area of land irrigated plus the cost of crop management, harvesting, storage, and transportation versus the value of the commodity produced) in a limited local market may exceed any realized economic gain.

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CHAPTER SEVEN

Conclusions and Recommendations

The commercial potential of some coals to serve as a source of natural gas has been realized only in the past three decades in the form of coalbed methane (CBM) production. The energy value of this resource can often be achieved by pumping water from water-saturated coal seams to reduce the pressure in the seam, allowing methane to desorb and flow to the surface. Thus, CBM production requires management of two important resources—natural gas and CBM "produced water."

Management of CBM produced water is a challenge for regulatory agencies, CBM operators, water treatment companies, policy makers, natural resource agencies, some landowners, and the public because produced water from CBM extraction represents a waste to some and is considered a beneficial byproduct of CBM activity by others. Furthermore, natural hydrogeological variations among and within CBM basins make a simple, single management approach to CBM produced water unrealistic. Presently, no collectively and clearly defined goals, objectives, management positions, or regulatory policies exist among federal and state agencies and other stakeholders regarding CBM produced water management and potential beneficial use.

The conclusions and recommendations in this chapter are directed toward identifying and resolving what the committee identifies as gaps—in data and information about CBM produced water geochemistry and basin hydrogeology, the effects of CBM production and produced water discharges on the environment, and the regulatory framework governing the management of CBM produced water. Resolving these gaps could increase the ability of stakeholders to continue to develop more effective and sound CBM development and produced water management practices. These recommendations also serve to reinforce efforts being made by individuals, regulatory authorities, operating companies, research institutions, and water treatment companies to monitor, analyze, regulate, and treat CBM produced water for disposal and/or beneficial use. The committee has examined the most prolific CBM basins—the Powder River, San Juan, Raton, Piceance, and Uinta located in five of the six western states identified for this study—New Mexico, Colorado, Utah, Wyoming, and Montana. North Dakota, which is also identified as a target for this study, does not have active CBM production at present. In examining the known and potential effects of CBM produced water discharges on the environment, the committee focused its efforts on the Powder River Basin, with its relatively shallow coalbeds and less saline produced water and management of CBM produced water primarily through disposal in surface impoundments and surface water.

CBM PRODUCED WATER HYDROGEOLOGY: THE IMPORTANCE OF ESTABLISHING HYDRAULIC CONNECTIVITY

The degree of hydraulic connectivity between water-bearing coalbeds targeted for methane production and shallow alluvial or water table aquifers that support human activities and natural habitats is an important factor in determining the consequences of water withdrawal during CBM extraction. In this context the concept of the age of the water in a coalbed is also significant because the age, or length of time the water has resided in the coalbed, is one indication of the degree to which the coalbed aquifer is connected to surface water and shallow groundwater. "Old" or "fossil" water in coalbeds is water that has not been replenished in the coalbed by infiltrating precipitation within human lifetimes or even thousands to millions of years. This lack of natural recharge may be due to discontinuities within coalbeds or between a coalbed and associated geological units, and/or to the location of recharge areas far from downgradient portions of a coalbed. Such fossil water can be considered a "nonrenewable" resource.

Thorough in situ physical studies to determine the degree of hydraulic connectivity between CBM aquifers and shallow groundwater aquifers have been completed only in the San Juan Basin. The data, including geochemical analyses to determine the age of the water, establish a lack of hydraulic connectivity between CBM aquifers and shallow groundwater resources. The great depths from which CBM and water are extracted in the Uinta and Piceance basins, relative to shallow groundwater systems in these areas, make widespread hydraulic connectivity unlikely. Existing data in the Raton and Powder River basins suggest a lack of widespread hydraulic connectivity between CBM aquifers and other groundwater aquifers, but these studies have been limited in scope and have been generally site specific. Consequently, the connectivity between coalbed water and other water resources is not well defined in most western CBM basins and leads to uncertainty in the consequence of long-term produced water withdrawals on other aquifers.

Mathematical models have been used to characterize the effects of CBM water withdrawal on surface water flows and shallow groundwater levels but have not been calibrated using actual measurements of drawdown in the surface water bodies or shallow aquifers. Such measurements can provide reliable inputs against which model results can be tested. Current mathematical models cannot yet characterize complex water/rock interactions, differences in hydraulic properties, or boundary conditions present in CBM basins with confidence, including the degree of interconnectivity between coalbeds, groundwater aquifers, and shallow alluvial aquifers. **Therefore, mathematical models used to characterize the effects of CBM water extraction on the connections between surface water and shallow groundwater aquifers should include independent geological, geochemical (including age dating), and hydrological measurements in CBM basins and watersheds as inputs to provide a level of reliability for model results. When noncalibrated models are used to make water management and regulatory decisions, their uncertainties should be explicitly recognized.**

Determining the age of CBM produced water—whether the water should be considered "fossil" water and thereby a nonrenewable resource—is a corollary benefit to conducting these kinds of measurements prior to modeling. **The scientifically established age of CBM produced water, and therefore its "renewability," should be considered in the development and implementation of CBM produced water management regulations.**

CBM PRODUCED WATER EFFECTS ON SURFACE WATER AND GROUNDWATER RESOURCES AND THE ENVIRONMENT

The potential effects on the environment of pumping and eventual disposal or use of CBM produced water relate to water quantity, through potential water drawdown or volume addition, and changes in water quality. Baseline water quantity or quality (conditions before CBM extraction begins) could change as a result of CBM operations and produced water management practices, depending on the relative quality of CBM produced water and baseline groundwater or surface water and whether produced water is being extracted or discharged in a given environment.

Groundwater Quantity and Quality

In the Powder River Basin, evidence of drawdown of water levels and hydrostatic heads has been documented in coalbed aquifers as a result of CBM production. However, drawdown effects on shallow groundwater aquifers as a result of CBM production have not, to the committee's knowledge, been publicly documented and substantiated. This lack of documented effect may be due, in part, to lack of hydraulic connection between coalbed aquifers and shallower aquifers that may be used for domestic water supplies, and in part to a lack of reliable baseline water level data. Thus, **resource management or regulatory agencies should require or continue to require collection of baseline groundwater level and quality information for domestic water wells in advance of new CBM drilling activities to protect well operators and residents.** These data can be compared against groundwater level and quality measurements made during and after CBM development.

Effects on groundwater quality from CBM produced water impoundments relate largely to leaching of salts, metals, or metalloids, such as sulfate, selenium, arsenic, manganese, barium, and total dissolved solids (TDS), which occur naturally in soils in or under many impoundments but may be dissolved and mobilized by CBM produced water infiltrating beneath the impoundments. Changes to groundwater quality in the Powder River Basin below and downgradient from CBM produced water impoundments were found in approximately one-third of the currently monitored impoundments. Changes involved increased levels of TDS, selenium, and sulfate. Some impoundments (lined and unlined) are also used in the Raton Basin in Colorado, and state authorities have reported leaks or seepage from the impoundments, either to surface water or groundwater. However, the committee was not able to identify specific data on the extent of any effects from impoundment seepage in the Raton Basin. The committee notes that few baseline data (prior to CBM development) on groundwater quality are available and that more time may have to elapse in the western CBM basins for effects on groundwater to be observed.

Groundwater monitoring networks and the capacity to maintain and analyze results from such networks are considered important for use and management of CBM produced water impoundments that are used for more than temporary storage. **Groundwater monitoring downgradient of impoundments used for disposal of CBM produced water before, during, and after water storage in the impoundments should be conducted and the data from these installations should be enhanced with (1) data on the volumes and chemistry of water discharged into impoundments, and (2) evaluation of the effects of impoundment infiltration or seepage on downgradient groundwater and nearby surface water.**

In the San Juan and Raton basins, no existing documentation shows adverse affects to groundwater quality from long-term reinjection of CBM produced waters. No empirical evidence was available from the Uinta and Piceance basins, but the committee concludes that the great vertical separation between sites of deep reinjection and groundwater aquifers, as well as the compartmentalization of the hydrogeological system in these basins, makes adverse effects unlikely.

Surface Water Quantity and Quality

Current surface water discharge permitting requires consideration of the quantity and quality of water in that receiving stream or river and the quantity and quality of discharged produced water. Measurements of the effects of CBM produced water discharges on the receiving stream or river quantity and quality are made periodically and can be used to regulate the discharge quantity and quality, if needed, to comply with permitted levels. **Measurements of the effects of CBM produced water discharges on receiving stream quality and quantity should be continued and rigorously used in setting regulatory requirements and permit limits by the appropriate state and federal authorities.**

In Wyoming, discharge volumes of CBM produced water at outfalls (end-of-pipe) are recorded periodically and some data are also collected at CBM outfalls in Montana. Actual volumes of water being discharged at most CBM outfalls in the basins studied vary as a normal function of CBM well operations. Produced water volume and chemistry data at outfalls are at present either infrequently collected, or are not available in an easily-accessible database. Knowledge of produced water volumes and chemistry at CBM produced water outfalls would allow operators and regulators to work in concert to monitor and predict anticipated needs for treatment, disposal, management and use of produced water. **In monitoring compliance, in modifying discharge allowances and permitted conditions, and in setting regulatory requirements, measurement of CBM produced water volumes and chemistry at outfalls should be collected regularly, reported, and made publicly accessible as a collaborative endeavor among industry, and state and federal authorities.** More regular monitoring and reporting would provide regulatory agencies, compliance officers, and researchers with more useful information than the periodic instantaneous data that are generally required at present.

Little evidence exists to substantiate that surface water has been depleted by pumping water during CBM production at the large watershed scale in the San Juan or Powder River basins. Managed-by-permit discharge of CBM produced water to ephemeral and perennial streams and rivers occurs only in the Powder River and Raton basins. At present, too few data, including background (historical) information on streamflows and climatic conditions, exist to evaluate positive or negative effects on water flows in streams and rivers in these two basins as a result of CBM produced water discharge.

Other physical effects to ephemeral or perennial streams and rivers, such as bank scouring, increased bottom sedimentation, or channel erosion, and to landscapes due to regulated, controlled, and managed, or unregulated and/or unmanaged CBM produced water discharges have been registered on private lands in the Powder River and Raton basins. Regulatory authorities have required operators to control and discontinue practices that have been shown to contribute to these physical effects. **Regulated (managed and controlled) releases to perennial and ephemeral streams and rivers and directly to the landscape should be accompanied by pre-release monitoring of landscape features, including stream channels. Regular monitoring of the same landscapes is necessary after releases have commenced.**

In parts of some perennial streams and rivers in the Powder River Basin, managed CBM produced water discharge has changed water chemistry. These changes are demonstrated by measurements of isotopic compositions of some solutes. However, the majority of studies on perennial drainages (Powder and Tongue rivers) found no discernable changes in surface water quality resulting from CBM inputs, using inorganic constituents, especially SAR and TDS, even when adjustments were made for changing climatic conditions. Specific conductance (as measure by TDS) and SAR may not be the most diagnostic measures of CBM produced water influence on receiving water bodies, particularly in the Powder River

Basin where rivers have natural salinity values close to those in CBM produced waters. **A larger array of chemical parameters, including major, minor and trace constituents and isotopes, should be used to evaluate the potential effects of CBM discharges on stream water quality.** The occurrence of comingling or presence of deep-injected CBM produced water in shallow groundwater in the San Juan, Raton, Piceance, or Uinta basins has not been documented.

Agricultural Applications

Use of some CBM produced waters for site-specific irrigation appears practical given appropriate conditions including availability of produced water and use of various combinations of selective application to nondispersive soils, treatment, dilution or blending of CBM produced water with other water sources; amendment of produced water and soils to be irrigated; and appropriate timing of irrigation practices. However, in the event that CBM produced water is discharged to perennial or ephemeral streams and rivers for the purpose of supplementing irrigation water supplies, careful consideration needs to be given to potential effects on instream water qualities. Suitability of CBM produced water for irrigation is site specific, thus necessitating identification of the most sensitive irrigable soils within the watershed and managing produced water discharges accordingly. After use of CBM produced water ceases, additional soil management will be required to restore impoundment sites and may be required to restore some soil agricultural resources to conditions that existed prior to CBM produced water application. Although CBM produced water does not represent an inexhaustible supply of water for irrigation, consideration may be given to use of CBM produced water as a supplement to irrigation, given appropriate conditions and management.

Ecological Effects

A number of controlled laboratory benchtop greenhouse studies and modeling efforts to examine potential effects of CBM produced water on some aquatic organisms have been published. These studies have indicated that water containing TDS and other ionic species above specific baseline levels may cause chronic distress in or be toxic to some organisms. However, widespread adverse effects on indigenous organisms and vegetation as a result of changes in surface water chemistry due to CBM produced water discharges in CBM basins have not been documented. At present, only limited published peer-reviewed research findings on in situ short- and long-term impacts of CBM produced water discharges on ephemeral and perennial stream channel ecology exist. **Studies to evaluate the extent and persistence of changes in water chemistry and ecological effects on indigenous species and hydrological systems *in the field*, including perennial riparian vegetation, stream**

hydrological function, stream channel geomorphology, macroinvertebrates, nutrient loading, and fisheries, should be conducted and the results used as input to review and enhance, as needed, CBM produced water management, treatment, and disposal requirements.

REGULATORY FRAMEWORK

The requirements associated with leasing and permitting CBM operations on federal and tribal lands through BLM and protecting water resources on federal, state, tribal, or private lands through the CWA and SDWA under EPA's jurisdiction are relatively broad, but clear. Specific provisions under the NPDES permitting process apply to disposal of produced waters to the surface, and the UIC program, under the SDWA, applies if subsurface reinjection of produced water for disposal is used. Federal agencies work in concert with state and tribal authorities to enforce the federal standards and regulations, and EPA has delegated primacy for some of these permitting and regulatory functions to relevant state and tribal authorities in the six western states examined in this study.

Regulations regarding treatment and management of CBM produced water differ among the states examined in this study, as do the degree to which the states have been delegated primacy by federal agencies for permitting and regulation of CBM produced water management. Recognizing the jurisdiction of Indian tribes in regulating CBM development and managing CBM produced water is also important. Although different approaches have been taken by states and tribes, the various governing authorities generally appear to try to work in concert in their efforts to negotiate the complexities of these interleaved regulations for the protection and preservation of clean and safe surface water and groundwater resources and environmental protection.

At present, a challenge to effective management of produced water is inconsistency in the definition and consideration of CBM produced water as either a waste or a "beneficial use" in the six western states. Identifiable beneficial opportunities for use of CBM water include irrigation, rangeland habitat improvement, livestock watering, alluvial aquifer recharge, aquifer storage, wildlife habitat enhancement, reclamation of well pads, industry applications, and potentially municipal use or consumption. CBM produced water volumes change over time and eventually decrease to near zero as development of CBM fields mature, making sustainability or long-term dependability of this water supply an issue in consideration of these beneficial use opportunities.

The committee concludes that management of CBM produced water is presently driven by regulations and economics of disposal and treatment costs relative to revenues generated from the sale of methane rather than consideration of the potential for beneficial use. Additionally, efforts to direct produced water management based on uncalibrated models need to be avoided.

Given that produced water can be treated to any water quality with current technologies but at widely varying costs, **future regulation of CBM produced water management should consider the age of the CBM produced water. Careful management of nonrenewable "fossil" water, after extraction, for best nonrenewable resource use should be considered a priority.**

Costs of water treatment, storage, and transport are not negligible, but current regulations and water law do not allow CBM operating companies or other stakeholders many options to consider other than disposal of fossil (nonrenewable) CBM produced water of relatively poor quality through deep-well injection. This kind of water management is not and should not be considered a beneficial use of the water resource. Even in cases such as the Powder River Basin where CBM produced water contains relatively low dissolved solids concentrations, the full range of beneficial use options is not exercised, partly due to economics and partly due to the restrictions of existing water law.

CLOSING REMARKS

Each beneficial use aligns with a set of criteria and acceptable or appropriate criteria for one beneficial use of CBM produced water may be in direct conflict with the criteria for another beneficial use. Additional complications are introduced when consideration is given to liability, water rights regulations, and sustainability of supply issues. These circumstances, in addition to the general decrease in volume of CBM produced water over the lifetime of a well, make CBM produced water an uncertainty and only a temporary source of water for beneficial use. This uncertainty contributes to the difficulty of addressing opportunities for beneficial use.

Recent litigation and changing case law in some western states related to CBM produced water management signal that various stakeholders now recognize the fact that water resources traverse state, legal, and geological boundaries. CBM production in the United States currently constitutes about 10 percent of annual domestic dry natural gas production and is predicted to grow as the nation considers the transition to a less carbon intensive energy resource base, of which natural gas is considered a cornerstone. Integrated approaches toward water and energy use and conservation are increasingly being considered as environmentally and economically sound. Multiple potential users and uses of limited water resources, a concern by the public for protection of these limited resources, the complexities of hydrogeological systems, and the renewability or nonrenewability of water resources require increasingly sophisticated approaches to CBM produced water management. These approaches require a basis in scientifically grounded studies and consistent monitoring and should allow for a greater range of economically and environmentally viable options for CBM produced water management.

Appendixes

APPENDIX A

Legislative Authorization Language H.R. 6—Energy Policy Act of 2005 Section 1811. Coal Bed Methane Study

Public Law 109-58

109th Congress
August 8, 2005
H.R. 6, Energy Policy Act of 2005.
42 USC 15801

SEC. 1811. COAL BED METHANE STUDY.

(a) STUDY.—Contracts.

(1) IN GENERAL.—The Secretary of the Interior, in consultation with the Administrator of the Environmental Protection Agency, shall enter into an arrangement under which the National Academy of Sciences shall conduct a study on the effect of coal bed natural gas production on surface and ground water resources, including ground water aquifiers, in the States of Montana, Wyoming, Colorado, New Mexico, North Dakota, and Utah.

(2) MATTERS TO BE ADDRESSED.—The study shall address the effectiveness of—

(A) the management of coal bed methane produced water;

(B) the use of best management practices; and

(C) various production techniques for coal bed methane natural gas in minimizing impacts on water resources.

(b) DATA ANALYSIS.—The study shall analyze available hydrologic, geologic and water quality data, along with—

(1) production techniques, produced water management techniques, best man-

agement practices, and other factors that can mitigate effects of coal bed methane development;

(2) the costs associated with mitigation techniques;

(3) effects on surface or ground water resources, including drinking water, associated with surface or subsurface disposal of waters produced during extraction of coal bed methane; and

(4) any other significant effects on surface or ground water resources associated with production of coal bed methane.

(c) RECOMMENDATIONS.—The study shall analyze the effectiveness of current mitigation practices of coal bed methane produced water handling in relation to existing Federal and State laws and regulations, and make recommendations as to changes, if any, to Federal law necessary to address adverse impacts to surface or ground water resources associated with coal bed methane development.

(d) COMPLETION OF STUDY.—The National Academy of Sciences shall submit the findings and recommendations of the study to the Secretary of the Interior and the Administrator of the Environmental Protection Agency within 12 months after the date of enactment of this Act, and shall upon completion make the results of the study available to the public.

(e) REPORT TO CONGRESS.—The Secretary of the Interior and the Administrator of the Environmental Protection Agency, after consulting with States, shall report to the Congress within 6 months after receiving the results of the study on—

(1) the findings and recommendations of the study;

(2) the agreement or disagreement of the Secretary of the Interior and the Administrator of the Environmental Protection Agency with each of its findings and recommendations; and

(3) any recommended changes in funding to address the effects of coal bed methane production on surface and ground water resources.

APPENDIX B

Committee and Staff Biographical Sketches

William L. Fisher (NAE), *Chair*, is a professor and the Leonidas T. Barrow Centennial Chair in Mineral Resources in the Department of Geological Sciences at the University of Texas at Austin. He has extensive experience in academia and in state and federal government, including service as Texas state geologist and director of the Bureau of Economic Geology, and as assistant secretary of the Department of the Interior. Dr. Fisher is past president of the Association of American State Geologists, American Association of Petroleum Geologists (AAPG), American Geological Institute (AGI), American Institute of Professional Geologists (AIPG), and Gulf Coast Association of Geological Societies. He has received the Powers Medal from AAPG, the Campbell Medal from AGI, the Parker Medal from AIPG, and the Hedberg Medal from the Institute for the Study of Earth and Man. His research interests include energy and mineral policy, basin analysis, energy and mineral resource evaluation, stratigraphic facies analysis, seismic stratigraphic analysis, oil and gas recovery, environmental geology, and waste disposal. Dr. Fisher is a former member of the NRC's Commission on Geosciences, Environment, and Resources, former chair of the Board on Earth Sciences and Resources, and a former member of the Board on Energy and Environmental Systems. Dr. Fisher was elected to the National Academy of Engineering in 1994.

James W. Bauder is a professor and soil-water specialist with the Department of Land Resources and Environmental Sciences at Montana State University (MSU), Bozeman, where he also serves as coordinator of the MSU Coalbed Methane Product Water Management/Outreach Education Project. His current work focuses on developing educational resources and materials for local government agencies and interested groups, with emphasis on groundwater quality, irrigation, management, and soil and water conservation. Dr. Bauder is a certified professional soils scientist. He has received numerous awards for his work, including the 2007 American Society of Agronomy International Agronomic Extension Educator Award. He earned a B.S. in forestry management and an M.S. in watershed science from the University of Massachusetts and a Ph.D. in soil physics and irrigation science from Utah State University.

William H. Clements is a professor in the Department of Fish, Wildlife, and Conservation Biology at Colorado State University. His research interests include aquatic ecology and ecotoxicology, community responses of aquatic organisms to contaminants, stressor interactions in aquatic ecosystems, and effects of climate change and ultraviolet radiation on streams. Dr. Clements is the author of two textbooks on ecotoxicology. He received the 2006 Presidential Citation from the Society of Environmental Toxicology and Chemistry. He previously served on the National Research Council Committee on Sediment Dredging at Superfund Megasites. Dr. Clements received his B.S. and M.S. in biology from Florida State University and his Ph.D. in zoology from Virginia Tech.

Inez Hua is a professor in the School of Civil Engineering at Purdue University, where she is also founding interim head of the Division of Environmental and Ecological Engineering, College of Engineering. Dr. Hua has completed research projects and published results on various aspects of industrial ecology and sustainability, water pollution control technologies, environmental chemistry, contaminant fate, and remediation technologies. One major theme in her research is technology development for water pollution control in which she has conducted research on innovative technologies such as supercritical water oxidation, ultrasonic irradiation, and engineered photochemical systems. Dr. Hua previously served as a member of the National Research Council Committee for the Technical Assessment of Environmental Programs at the Los Alamos National Laboratory. Dr. Hua received a B.A. in biochemistry from the University of California, Berkeley, and M.S. and Ph.D. degrees in environmental science and engineering from the California Institute of Technology.

Ann S. Maest is an aqueous geochemist with Stratus Consulting, Inc., in Boulder, Colorado, where she designs, conducts, and manages groundwater and surface water hydrogeochemistry studies at mining and other industrial sites. She also works on independent monitoring and capacity-building projects with community and indigenous groups in North and South America. With expertise in the fate and transport of natural and anthropogenic contaminants in groundwater, surface water, and sediment, her work has focused on the environmental effects of mining and petroleum extraction and production and, more recently, on the effects of climate change on water quality. Before joining Stratus Consulting, Dr. Maest was a research geochemist with the U.S. Geological Survey in Menlo Park, California, where she conducted research on metal speciation, and a senior scientist at Environmental Defense in Washington, D.C., where she designed technical and policy approaches to minimize the release of toxic substances from mining and manufacturing facilities. Dr. Maest has served on a number of national and international committees, including three National Research Council committees related to earth resources and minerals research and international committees on mining and sustainable development. She holds a Ph.D. in geochemistry and water resources from Princeton University and an undergraduate degree in geology from Boston University.

Arthur W. Ray currently serves as the president of Wiley Environmental Strategies, a minority-owned environmental consulting firm. He has been engaged with the firm since 2001, with exception of a short period as a senior regulatory analyst and environmental justice coordinator for the District Department of the Environment (DDOE) in Washington, D.C. From 1995 until 2001 he served as deputy secretary of the Maryland Department of the Environment, where he directed all aspects of pollution control and environmental protection in the state. He has also served in legal and managerial capacities at three major utility companies, assisting each company's environmental compliance efforts. Mr. Ray worked in the Office of Enforcement at the U.S. Environmental Protection Agency from 1979 to 1990, during which time he was involved in the prosecution of major hazardous waste enforcement cases. A recognized expert in the field of environmental justice (EJ), Mr. Ray has been the lead attorney in several groundbreaking EJ enforcement actions. He has done extensive work with EJ community groups throughout the country and has assisted in setting up EJ programs for businesses and government agencies. He received his B.A. from Brown University and a J.D. from George Washington University.

W. C. "Rusty" Riese is a geoscience advisor with British Petroleum Alternative Energy and has more than 37 years of industry experience in both nonfuel and fuel minerals as a geologist, geochemist, and manager. Dr. Riese has written extensively and lectured on various topics in applied science, including biogeochemistry, geomicrobiology, isotope geochemistry, uranium ore deposits, sequence stratigraphy, and coalbed methane petroleum systems, and holds numerous domestic and international patents, most developed during his 15 years of coalbed methane work and research. He has more than 30 years of teaching experience, including 24 years at Rice University where he developed the curricula for petroleum geology and industry risk and economic evaluation. Dr. Riese participated in the National Petroleum Council (NPC) evaluation of natural gas supply and demand for North America, conducted at the request of the secretary of the U.S. Department of Energy and in the recent NPC analysis of global supply and demand requested by the same agency. He is a member of the house of delegates and is sections vice president for the American Association of Petroleum Geologists and a fellow of the Geological Society of America and the Society of Economic Geologists. A certified professional geologist, certified petroleum geologist, and registered geologist in the states of Texas and South Carolina, Dr. Riese earned his B.S. in geology from the New Mexico Institute of Mining and Technology and both his M.S. and Ph.D. in geology from the University of New Mexico.

Donald I. Siegel is a professor of geology at Syracuse University, where he teaches graduate courses in hydrogeology and aqueous geochemistry. Prior to his professorship at Syracuse, he was a hydrologist at the U.S. Geological Survey. His research interests are in solute transport at both local and regional scales, surface water/groundwater interaction, stable isotope geochemistry, and paleohydrogeology. Dr. Siegel was awarded the Distinguished Service Award, the O. E. Meinzer Award, and the Birdsall-Dreiss Lectureship by the Hydrogeology Division of the Geological Society of America (GSA). He recently served as a counselor of GSA and has served or serves as associate editor of numerous professional journals, including *Geology*, *Hydrologic Processes*, *Water Resources Research*, the *Hydrogeology Journal* and *Geosphere*. He now is book editor for GSA. He has served on numerous NRC committees, including the Committee on Wetlands Characterization, Committee on Techniques for Assessing Ground Water Vulnerability, and Committee on River Science at the U.S. Geological Survey. Recently, Dr. Siegel was awarded a lifetime national associate designation by the National Research Council for his contributions. He holds B.S. and M.S. degrees in geology from the University of Rhode Island and Pennsylvania State University, respectively, and a Ph.D. in hydrogeology from the University of Minnesota.

Geoffrey Thyne is a registered professional geologist and senior research scientist at the Enhanced Oil Recovery Institute (EORI) at the University of Wyoming. He has worked as a research scientist for Arco Oil and Gas; as assistant professor at California State University, Bakersfield in the Department of Physics and Geology; and as associate research professor at the Colorado School of Mines Department of Geology and Geological Engineering. He also served as project manager for the Colorado Energy Research Institute, supervising a U.S. Department of Energy-funded project to evaluate various water treatments for coalbed methane produced water. Before joining the EORI, he worked on a variety of research and consulting projects in the western United States involving impacts of energy production on water resources. He has authored of more than 35 peer-reviewed scientific papers and has given many professional presentations. Dr. Thyne holds a B.A. in chemistry and zoology from the University of South Florida, an M.S. in oceanography from Texas A&M University, and a Ph.D. in geology from the University of Wyoming.

NRC Staff

Elizabeth A. Eide is a senior program officer with the Board on Earth Sciences and Resources. Prior to joining the NRC in 2005, she was as a research scientist for 12 years at the Geological Survey of Norway where she was team leader and built and managed the $^{40}Ar/^{39}Ar$ geochronology laboratory. Her research while in Norway included basic and applied projects related to crustal processes. She completed a Ph.D. in geology at Stanford University and received a B.A. in geology from Franklin and Marshall College.

Stephanie E. Johnson is a senior program officer with the Water Science and Technology Board. Since joining the NRC in 2002, she has served as study director for 10 committees, including the Committee on Advancing Desalination Technology and the Committee on Water Reuse. She has also worked on NRC studies on contaminant source remediation, disposal of coal combustion wastes, Everglades restoration, and water security. Dr. Johnson received her B.A. from Vanderbilt University in chemistry and geology and her M.S. and Ph.D. in environmental sciences from the University of Virginia on the subject of pesticide transport and microbial bioavailability in soils.

Courtney R. Gibbs is a program associate with the Board on Earth Sciences and Resources. She received her degree in graphic design from the Pittsburgh Technical Institute in 2000 and began working for the National Academies in 2004. Prior to her work with the board, Ms. Gibbs supported the Nuclear and Radiation Studies Board, the former Board on Radiation Effects Research, and the Naval Studies Board.

Jason R. Ortego is a research associate with the Board on Earth Sciences and Resources. He received a B.A. in English from Louisiana State University in 2004 and an M.A. in international affairs from George Washington University in 2008. He began working for the National Academies in 2008 with the Board on Energy and Environmental Systems, and in 2009 he joined the Board on Earth Sciences and Resources.

Nicholas D. Rogers is a research associate with the Board on Earth Sciences and Resources at the National Academies. He received a B.A. in history, with a focus on the history of science and early American history, from Western Connecticut State University in 2004. Mr. Rogers began working for the National Academies in 2006 and has primarily supported the Board on Earth Sciences and Resources on earth resource issues and the board's interdisciplinary projects.

APPENDIX C

Presentations to the Committee

Meeting One—Washington, D.C.

Ray Brady, Bureau of Land Management, *Overview of the requirements of Section 1811 of the Energy Policy Act and the statement of work with some highlights of the key points for the study*

James Burd, Bureau of Land Management, *Background on CBM development and an overview of existing studies*

Carey Johnston, U.S. Environmental Protection Agency, *Update on EPA's Clean Water Act review of the coalbed methane industrial sector*

Meeting Two—Denver, Colorado

Ralf Topper, Colorado Geological Survey, *CBM produced water—A waste or resource?*

Kevin Rein, Colorado Division of Water Resources, *Overview: Water rights and administration of produced water in Colorado*

Dave Stewart, Stewart Environmental Consultants, Inc., *Practical considerations for beneficial use of produced water*

Curtis Brown, Bureau of Reclamation, *Produced waters: Intersection with Bureau of Reclamation programs*

John Boysen, BC Technologies, *Emerging technologies for CBM produced water treatment and disposal*

Don Fischer, Wyoming Department of Environmental Quality, *Summary of coalbed natural gas management facilities*

John Wheaton, Montana Bureau of Mines and Geology, *Lessons learned from a regional groundwater monitoring program, Powder River Basin, Montana*

Helen Dawson, U.S. Environmental Protection Agency, *Analysis of CBM produced water discharge on surface water quality in the Powder River Basin through water year 2005*

Public comments

Meeting Three—Santa Fe, NM

Mark Fesmire, New Mexico Oil Conservation Commission, *History and overview of coal bed methane production and CBM produced water in New Mexico*

David Mankiewicz, Bureau of Land Management, Farmington, *Coalbed methane produced water in the San Juan Basin, New Mexico*

Carol Frost, University of Wyoming, *Assessing the impact of CBM produced water on shallow aquifers and surface water: An environmental isotope approach*

James Keener, Red Willow Production Company, *Red Willow Production Company's management of produced water from CBM, "On Reservation"*

David Brown, BP America, *Oil and gas exploration and production perspective: Management of produced water in the San Juan Basin of Colorado*

APPENDIX D

Information Inventory

This appendix provides a relatively complete but not exhaustive record of the types of research and studies being conducted by various federal, state, and other entities with respect to coalbed methane (CBM) produced water effects and management. Many of the resources and references listed are also incorporated into discussions in various chapters of the report. The reader is referred to the resources themselves, which often contain their own extensive reference lists not detailed in this appendix.

FEDERAL DATA RESOURCES

Bureau of Land Management

The BLM is primarily engaged with resource characterization, including publication of an extensive database on potential CBM reserves.[1] As part of the CBM permitting process and often in collaboration with the U.S. Department of Agriculture's Forest Service, data from the U.S. Geological Survey, states, and other research sources are included in Environmental Impact Statements (EISs), Environmental Assessments, Resource Management Plans (RMPs), and Reasonable Foreseeable Development scenarios produced by BLM. These documents are generally coordinated by the relevant BLM field offices. Examples that addressed western CBM production include the following:

- Northern San Juan Basin Coalbed Methane Draft EIS Released for Public Review;[2]

[1]See gswindell.com/blmcoalb.htm (accessed March 23, 2010).
[2]See www.blm.gov/co/st/en/BLM_Information/newsroom/2004/northern_san_juan.html (accessed March 23, 2010).

- Powder River Basin Oil & Gas Project EIS;[3]
- Oil and Gas Leasing Environmental Assessment 070-05-064 (BLM, 2005);
- Wyodak Drainage Coal Bed Methane Environmental Assessment WY-070-01-034 (BLM, 2001); and
- Farmington Resource Management Plan.[4]

BLM has supported projects in conjunction with states and other researchers, either in support of RMPs (e.g., Engler et al., 2001) or as stand-alone studies (e.g., ALL Consulting, 2003; Wheaton and Metesh, 2001, 2002; Cox et al., 2001). Financial support for groundwater monitoring wells is also provided by BLM to Montana, for example, in support of that state's groundwater monitoring activities, some of which are associated with CBM production areas (see Chapter 5).

U.S. Environmental Protection Agency

The EPA is conducting a comprehensive, industry-wide review and data collection of produced water quality and quantity, treatment and management alternatives and costs, treatment technologies, water production, and discharge volumes associated with CBM production[5] (see also Box 3.2 in Chapter 3). EPA reviews and studies are also addressing potential environmental impacts of CBM water discharges to biota and soils. Additionally, the EPA has investigated how hydraulic fracturing of water-saturated coalbeds containing methane may affect water quality.[6] EPA (2004) and EPA (2006) each describe some of these activities in greater detail. In the past, EPA's National Center for Environmental Research has also provided support to external research projects on topics related to CBM produced water.[7,8]

U.S. Geological Survey

The USGS has established a significant role in data collection, compilation, analysis, interpretation, and reporting, with particular focus on perennial water resources, produced water quality, and hydrogeological processes associated with CBM and produced water. This work is being done under the auspices of the USGS Energy Resources Program, in

[3]See www.blm.gov/wy/st/en/info/NEPA/bfodocs/prb_eis.html (accessed March 23, 2010).
[4]See www.blm.gov/nm/st/en/fo/Farmington_Field_Office/farmington_rmp.html (accessed March 23, 2010).
[5]See "Coalbed Methane Extraction Detailed Study" at www.epa.gov/guide/cbm/ (accessed March 23, 2010).
[6]See www.epa.gov/OGWDW/uic/wells_coalbedmethanestudy.html (accessed March 23, 2010).
[7]See cfpub.epa.gov/ncer_abstracts/index.cfm/fuseaction/display.abstractDetail/abstract/1317/report/0 (accessed March 23, 2010).
[8]See cfpub.epa.gov/ncer_abstracts/index.cfm/fuseaction/display.abstractDetail/abstract/7722/report/0 (accessed March 23, 2010).

cooperation with the BLM, state agencies, colleges and universities, and other parties, with a primary goal to develop models to help access the methane resource and evaluate environmental implications of its development in the major coalbed regions in the United States.

To date, USGS scientists have published approximately 100 reports and results of research investigations on CBM and associated issues, ranging from circulars highlighting issues for the public (e.g., Nuccio, 2000; Rice and Nuccio, 2000) to a range of Water-Resources Investigations Reports, Open-File Reports, and Professional Papers (e.g., USGS, 2005). With respect to water quality issues, reports have been published on the chemical variability of Powder River Basin formation waters (e.g., Rice and Nuccio, 2000) and how produced water quality may relate to groundwater hydraulics and age of fluids in the CBM system (Bartos and Ogle, 2002). More broadly, the USGS toxic substances hydrology program has published a bibliography of research on petroleum-related produced water contamination (not CBM specific).[9]

In 2004 the USGS embarked on a long-term monitoring program in the Tongue River watershed of Wyoming and Montana to determine whether CBM production affects streamwater quality and quantity (see Chapter 5). This study, the Tongue River Surface-Water-Quality Monitoring Network,[10] conducted in cooperation with BLM, the Montana Department of Natural Resources and Conservation, the Northern Cheyenne Tribe, the T&Y Irrigation District, Fidelity Exploration, Montana and Wyoming Departments of Environmental Quality, and the Wyoming State Engineer's Office, involves real-time monitoring, periodic water quality sampling and characterization, and water quantity measurement at 12 locations within the Tongue River watershed, now part of the USGS National Stream Information Program. Many of these data are real time and are accessible via the Internet, including a broad suite of chemical parameters. Also available as an outcome of monitoring by the USGS are data on groundwater levels and streams in numerous basins being developed for CBM.[11]

The USGS has compiled a publically available national database of the analyzed chemistry of over 58,000 samples of waters sourced from hydrocarbon production, including CBM production,[12] and a bibliography of publications dealing with problems associated with the produced formation water (Otton, 2006), including effects of releases into ephemeral and perennial water bodies on the hydrology. The report includes a link to CBM production water data and other sources outside the agency.[13]

[9]See toxics.usgs.gov/bib/bib-PH2O.html (accessed March 23, 2010).
[10]See mt.water.usgs.gov/projects/tongueriver/ (accessed March 23, 2010).
[11]See water.usgs.gov/osw/ (accessed March 23, 2010).
[12]See energy.cr.usgs.gov/prov/prodwat/ (accessed March 23, 2010).
[13]See energy.cr.usgs.gov/oilgas/cbmethane/learnmore.html#links (accessed March 23, 2010).

U.S. Department of Energy

The DOE has played a significant role in promoting, supporting, and endorsing basic and applied research related to CBM. Most of these efforts and the resulting data have been sponsored by the National Energy Technology Laboratory (NETL) and/or performed in collaboration with Argonne National Laboratory or Sandia National Laboratories. The DOE maintains an extensive archive of information detailing energy resources, water resources, technical reports, and research summaries. Particular emphasis has been focused on approaches to CBM produced water, including techniques for downhole gas-water separation, bioremediation techniques associated with production water, industrial water treatment techniques, and alternatives for beneficial use of produced water. Much of this information is contained in the Produced Water Management Information System.[14]

NETL has coordinated support for research projects on the topic of produced water related to oil and gas development (not only for CBM).[15] Other studies or reports sponsored by DOE's Office of Fossil Energy and/or NETL related to produced water from oil and gas or specific to CBM include those by Veil et al. (2004), Advanced Resources International (2002), and ALL Consulting (2002). Work at Sandia National Laboratories has focused primarily on beneficial uses for CBM produced water in the San Juan Basin (Hightower, 2003).

The Energy Information Administration is the primary statistical agency responsible for collecting data and providing analysis of CBM exploration and reserves, production, and consumption.[16]

STATE AND OTHER DATA RESOURCES

State Agencies

State offices are often the first lines of consultation regarding state-specific CBM produced water data and analysis, and these offices work in collaboration with federal authorities. State natural resource management agencies in each of the respective states where CBM is commercially being recovered are actively engaged in data collection and compilation, research, reporting, and providing the public, academia, private consultants, and industry representatives access to such data. Chapter 3 describes the primary state agency and office functions and responsibilities in the western states where CBM and produced water are regulated and managed and provides Website information for these offices. State

[14] See www.netl.doe.gov/technologies/pwmis/index.html (accessed March 23, 2010).
[15] See www.netl.doe.gov/technologies/oil-gas/Projects/ENV_TOC.html#Produced (accessed March 23, 2010).
[16] See www.eia.doe.gov/oil_gas/natural_gas/info_glance/natural_gas.html (accessed March 23, 2010).

geological surveys, not described in any detail in Chapter 3, are also significant contributors to research in the following areas:

- Colorado State Geological Survey;[17]
- Montana Bureau of Mines and Geology;[18]
- New Mexico Bureau of Geology and Mineral Resources;[19]
- North Dakota Geological Survey;[20]
- Utah Geological Survey;[21] and
- Wyoming State Geological Survey.[22]

Interagency (federal and state) and interstate working groups also address produced water management issues and have supported research or compiled handbooks on related topics:

- Powder River Basin Interagency Working Group;[23]
- Western Governors' Association (WGA, 2006); and
- Western States Water Council.[24]

University Research

Numerous university research groups and nonprofit organizations actively conduct research on CBM and produced water effects and management. The research areas include agricultural sciences, biological sciences, civil engineering, ecology, environmental sciences, geosciences, hydrological sciences, and law. These resources include the following:

- Colorado School of Mines;[25]
- Colorado State University;[26]
- Montana State University;[27]

[17]See geosurvey.state.co.us/ (accessed March 23, 2010).
[18]See www.mbmg.mtech.edu/ (accessed March 23, 2010).
[19]See geoinfo.nmt.edu/about/home.html (accessed March 23, 2010).
[20]See www.dmr.nd.gov/ndgs/ (accessed March 23, 2010).
[21]See geology.utah.gov/ (accessed March 23, 2010).
[22]See www.wsgs.uwyo.edu/ (accessed March 23, 2010).
[23]See www.wy.blm.gov/prbgroup/docs/aquatics/index.htm (accessed March 23, 2010).
[24]See www.westgov.org/wswc/ (accessed March 23, 2010).
[25]See, e.g., ese.mines.edu/; www.aqwatec.com/; geophysics.mines.edu/; and geology.mines.edu/index.html (accessed March 23, 2010).
[26]See, e.g., warnercnr.colostate.edu/; warnercnr.colostate.edu/fwcb-home/; and www.engr.colostate.edu/cheme/index.shtml (accessed March 23, 2010).
[27]See waterquality.montana.edu/docs/methane.shtml (accessed March 23, 2010).

- New Mexico Institute of Mining and Technology;[28]
- New Mexico State University;[29]
- University of Colorado;[30]
- University of Montana;[31]
- University of New Mexico;[32]
- University of Utah;[33]
- University of Wyoming;[34] and
- Utah State University.[35]

[28] See www.ees.nmt.edu/; baervan.nmt.edu/; and infohost.nmt.edu/~enve/ (accessed March 23, 2010).

[29] See www.nmsu.edu/~geology/; eppws.nmsu.edu/; aces.nmsu.edu/academics/pes/index.html; wrri.nmsu.edu/ (accessed March 23, 2010).

[30] See www.colorado.edu/engineering/even/water.htm; www.colorado.edu/GeolSci/; www.colorado.edu/eeb/; and www.colorado.edu/law/centers/nrlc/ (accessed March 23, 2010).

[31] See www.cas.umt.edu/casweb/departments/dbs.cfm; www.cas.umt.edu/casweb/departments/geosciences.cfm; and www.cas.umt.edu/casweb/departments/evst.cfm (accessed March 23, 2010).

[32] See epswww.unm.edu/; www.unm.edu/~wrp/; and lawschool.unm.edu/natres-envlaw/index.php (accessed March 23, 2010).

[33] See www.civil.utah.edu/research.html; www.earth.utah.edu/?pageId=3816; and www.law.utah.edu/ (accessed March 23, 2010).

[34] See www.uwyo.edu/enr/ienr/; geology.uwyo.edu/; eori.gg.uwyo.edu/; www.uwyo.edu/ser/; and uwadmnweb.uwyo.edu/law/ (accessed March 23, 2010).

[35] See www.cee.usu.edu/; www.cnr.usu.edu/wats/; geology.usu.edu/ (accessed March 23, 2010).

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APPENDIX E

Historical Significance of a Water "Compact": Development of the Colorado Compact and the Upper Colorado River Basin Compact

Although no national water rights system exists in the United States, recognition of the continuity of surface water hydrology in the form of the Colorado River across many western states led to the development of the Colorado River Compact (45 Stat. 1057) in 1922. This compact forms an overarching background to decisions that impact surface water flows in western "headwater" states where flow originates.

In the early 1900s, water rights legislation was confusing and conflicts arose among the Colorado River states (see figure below). The root cause of these conflicts is the hydrologic reality that, although roughly 90 percent of the river's flow originates in the upper basin states of Colorado, New Mexico, Utah and Wyoming, much of the demand for the river's water emanates from the lower basin states of Arizona, California and Nevada (NRC, 2007). States claimed exclusive authority to regulate appropriation of stream water within their borders and the federal government claimed jurisdiction over water in interstate streams (Goslin, 1978). California, Nevada, and Arizona were proposing to store water in their states to offset seasonal flow variability and drought. They sought federal financing to create a comprehensive basin-wide development that would permit optimum use of the lower Colorado River. Colorado, Utah, Wyoming, and New Mexico officials argued that, without protective guarantees, the ability to use water in the future would be prevented. Therefore, establishing an agreement between the seven basin states regarding allocation of the Colorado River's waters was determined to be a necessity.

In 1922, the Colorado River Compact (45 Stat. 1057) was signed. The compact instituted the following: (1) annual beneficial consumptive use of 7.5 million acre-feet of water apportioned to each sub-basin with the lower basin granted the right to use another million acre-feet annually if it is available, and (2) recognition of the rights of Mexico to use water with each basin designated to provide water for one-half of any deficiency that might occur in any amount granted to Mexico by future international treaty. The upper division states were not to cause the flow of the Colorado River at Lee's Ferry to be less than 75 million acre-feet in any period of ten consecutive years (Goslin, 1978).

The compact cleared the way for federally funded, water-project development in the lower states, while allowing the upper states to develop at a slower pace without losing their water use rights. Since the 1890s, when direct stream flow measurements were made on the river, "the flow estimates on which allocations were negotiated in the 1920s were based upon data drawn from a relatively short and very wet period, and thus turned out to be overly optimistic" (NRC, 2007: 28). In fact, the gauge record shows that the 1905–1922 period had the highest annual flow volume of the 20th century, averaging 16.1 million acre-feet at Lee's Ferry.

The Rio Grande, Colorado and Tijuana Treaty of 1944 between the United States and Mexico (59 Stat. 1219, T.S. 994) codified obligations of the United States to deliver water from the Colorado River to Mexico and guaranteed that the United States would deliver to Mexico 1.5 million acre-feet annually of the "waters of the Colorado River, from any and all sources" (IBCW, 1944).[1] The treaty further provided that Mexico shall not acquire any right to water in excess of that amount thus preventing future Mexican demands for water as their agricultural water demands grew. The guaranteed 1.5 million acre-feet annual water delivery to Mexico was subject to reduction in the event of shortages or drought upstream in the U.S. portion of the basin. This treaty did not address water quality levels for the Colorado River water entering Mexico.

In 1949, the Upper Colorado River Basin Compact (63 Stat. 31) was signed, which apportioned water rights among the states with land in the upper basin. This compact details the rules and regulations for water-use curtailment during years when necessary to meet delivery requirements to the lower basin states under the Colorado River Compact. The compact specifies that the amount of water delivered at Lee's Ferry be "measured by the inflow-outflow method in terms of man-made depletions of the virgin flow" at that location (Goslin, 1978).[2] This compact also outlines agreements between member states (Colorado, Utah, Wyoming, and New Mexico) on the use of interstate stream water. Although technically part of the lower basin, a small portion of Arizona resides in the upper basin. That portion of Arizona was apportioned a fixed quantity of 50,000 acre-feet per year. The remaining water was divided as follows: Colorado with 51.75 percent, Utah with 23 percent, Wyoming with 14 percent, and New Mexico with 11.25 percent.

[1] See waterplan.state.wy.us/BAG/green/briefbook/lor/lor-7.html (accessed March 31, 2010).

[2] See Article VI of the Colorado River Compact at waterplan.state.wy.us/plan/green/techmemos/compacts.html (accessed March 31, 2010).

FIGURE E.1 Map of the Colorado River system includes upper and lower basins. SOURCE: © International Mapping Associates.

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APPENDIX F

Tribal Management of Coalbed Methane Development and Produced Water

Coalbed methane (CBM) development on tribal lands is governed by the Omnibus Indian Mineral Leasing Act of 1938 and the Indian Mineral Development Act of 1982 (see Chapter 3). In a manner similar to that used elsewhere in the report, tribal approaches to CBM production and produced water management were examined in areas where tribal CBM production activity is greatest and/or concerns over CBM produced water are most marked—in the San Juan and Powder River Basins. Examples of differing approaches to CBM development and produced water management by tribal governments are discussed below.

SAN JUAN BASIN

The Southern Ute Indian Tribe (SUIT) in Colorado, and the Navajo Nation and the Jicarilla Apache Nation in New Mexico have various levels of active CBM production on their lands in the San Juan Basin (DOE, 2010), although total CBM production on Navajo and Jicarilla Apache lands in the southern San Juan Basin appears limited at this time (Jones, 2010). In contrast, a significant proportion of the northern San Juan Basin in Colorado lies within SUIT lands. Companies operating on SUIT lands to develop CBM include the Red Willow Production Company, BP America, ConocoPhillips, Chevron Texaco, and XTO. Red Willow is wholly owned by the SUIT and is the main CBM operator on SUIT lands. Information provided to the committee by Red Willow—not on behalf of the SUIT—offers insight as to how CBM produced water is managed under tribal jurisdiction in the San Juan Basin.[1]

Red Willow operates a total of 414 CBM wells, 180 of which are on a reservation in Colorado. On-reservation wells produce 3,000 barrels of water per day, which represent

[1]J.B. Keener, Red Willow Production Company, presentation to the committee, June 2, 2009.

approximately 2 percent of the CBM water produced annually in the San Juan Basin.[2] The primary produced water management method used by Red Willow is reinjection. An estimated 25 percent of the CBM produced water is hauled by truck to a disposal well or facility, where wells inject into deep nonproducing formations 4,600 to 9,500 feet below ground surface. The remaining water is pumped through a network of underground pipes, some extending as far as 10 miles, to be injected into water disposal wells (WDWs). Each well is permitted through the Environmental Protection Agency's Underground Injection Control Program, and each permit has specific requirements for maximum allowable injection pressure. All permits require annual reporting on volumes disposed, injection pressures, and financial assurance. The Southern Ute Department of Natural Resources Water Resources Division provides for the management, conservation, and use of the tribe's surface water and groundwater resources. This work includes the installation of water measuring devices, implementation of soil and water conservation projects, protection of existing water rights, acquisition of new water rights, and strategic planning for the continuing development of water resources to benefit the tribal membership.[3]

Red Willow uses chemical treatments, such as paraffin dispersant, scale inhibitors, biocides, and corrosion inhibitors, to reduce clogging of filters at inlets to disposal wells and to prevent pressure buildup in WDWs (due to plugging with suspended solids). Some of these chemicals may enter the produced water stream; however, they are exempt from regulation under the Resource Conservation Recovery Act, which governs the disposal of hazardous and nonhazardous solid wastes.

Red Willow is involved with a project aimed to put CBM water to beneficial use. The SUIT Growth Fund Alternative Energy Group recently partnered with a biofuels company to use small portions (approximately 100 barrels) of Red Willow's CBM produced water to grow algae, which is converted to oil feedstock that can be refined into diesel fuel. Red Willow will dispose of wastewater product from the process. This plan will require modification of a Class II permit to a more rigorous Class I permit. If the pilot project is successful, this industrial process may utilize all of Red Willow's produced water.

POWDER RIVER BASIN

At the time of the writing of this report, no CBM production has occurred on the lands of either the Northern Cheyenne or the Crow Tribes in the Powder River Basin of Montana. Although both tribes have taken active steps to examine the possibility of developing CBM on their lands, they do not currently participate in CBM development nor are they involved in CBM produced water disposal. The Crow Tribe, for example, has articulated

[2]An estimated 46 million barrels of CBM water was produced in the San Juan Basin in 2008. See Chapter 2, Table 2.1.

[3]See www.southern-ute.nsn.us/DNRWeb/water.htm (accessed April 13, 2010).

environmental concerns with regard to CBM development, including potential effects to water quality and quantity, soil, and biota receiving CBM discharges as the tribe weighs the advantages and disadvantages of potential CBM development on their lands.[4]

The Northern Cheyenne Tribe has also expressed considerable concern about potential impacts of CBM development and produced water management on water resources of the Tongue River drainage in the Powder River Basin, including CBM development and produced water disposal that occurs outside the boundaries of their lands (e.g. Wo et al., 2004).[5] In 2006, the tribe received approval from the Environmental Protection Agency (EPA) to administer Clean Water Act programs and began developing its own surface water quality standards, applicable to the Tongue River and its tributaries within the boundaries of the reservation. Information indicates that in many cases the proposed standards are more stringent than the Montana state standards. The tribe developed these standards in part as a response to industry development of CBM wells on the Wyoming side of the Powder River Basin.[6] These standards are presently being reviewed by EPA and the Northern Cheyenne recently received approval from EPA to recirculate their standards for public comment. The Northern Cheyenne have also sided with State of Montana on litigation over Wyoming infringement on Montana water rights and violations of terms of Yellowstone Compact (SCOTUS, 2010).

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[4]See serc.carleton.edu/research_education/nativelands/crow/impacts.html (accessed July 15, 2010).

[5]See e.g., www.cheyennenation.com/tribalreport/June/The%20Nation%20page%204.htm (accessed February 2010) and www.osti.gov/bridge/product.biblio.jsp?osti_id=910962 (accessed June 2010).

[6]See missoulian.com/news/state-and-regional/article_4566099e-8772-11de-8a85-001cc4c03286.html (accessed July 15, 2010).

APPENDIX G

Acronyms and Abbreviations

ASR	aquifer storage and recovery
ATG	(Powder River) Aquatic Task Group
BER	Board of Environmental Review
BLM	Bureau of Land Management
CBM	coalbed methane
CBNG	coalbed natural gas (i.e., coalbed methane)
COGCC	Colorado Oil and Gas Conservation Commission
COGIS	Colorado Oil and Gas Information System
CWA	Clean Water Act
DEQ	(Wyoming) Department of Environmental Quality
DIC	dissolved inorganic carbon
DIN	dissolved inorganic nitrogen
DNR	(Utah) Department of Natural Resources
DNRC	Department of Natural Resources and Conservation
DOGM	(Utah) Division of Oil, Gas, and Mining
DWR	(Colorado) Division of Water Resources
DWRi	(Utah) Division of Water Rights
EA	environmental assessment
EC	electrical conductivity
EIA	Energy Information Administration
EIS	environmental impact statement
EPA	U.S. Environmental Protection Agency

FTE	Freeze/Thaw Evaporation
GPC	Groundwater Pollution Control
IOGCC	Interstate Oil and Gas Compact Commission
LPR	Little Powder River
MBMG	Montana Bureau of Mines and Geology
MBOGC	Montana Board of Oil and Gas Conservation
MPDES	Montana Pollutant Discharge Elimination System
NDIC	North Dakota Industrial Commission
NEPA	National Environmental Policy Act
NETL	National Environmental Technology Laboratory
NMED	New Mexico Environment Department
NPDES	National Pollutant Discharge Elimination System
NRC	National Research Council
OCD	Oil Conservation Division
OOGO	Onshore Oil and Gas Order
PAH	polycyclic aromatic hydrocarbons
PR	Powder River
PWMIS	Produced Water Management Information System
RO	reverse osmosis
RPSEA	Research Partnership to Secure Energy for America
SAR	sodium-adsorption ratio
SDI	subsurface drip irrigation
SDWA	Safe Drinking Water Act
SEO	State Engineer's Office
SWQB	(New Mexico) Surface Water Quality Bureau
TIE	toxicity identification and evaluation
TDS	total dissolved solids
TOC	total organic carbon
TR	Tongue River

UIC	Underground Injection Control
USDW	underground source of drinking water
USFS	U.S. Department of Agriculture Forest Service
USGS	U.S. Geological Survey
WQB	Water Quality Board
WQCC	(New Mexico) Water Quality Control Commission
WQCD	(Colorado) Water Quality Control Division
WQS	water quality standards
WSGS	Wyoming State Geological Survey
WYPDES	Wyoming Pollutant Discharge Elimination System

UNITS

$\delta^{13}C_{dic}$	delta 13; the difference between the ($^{13}C/^{12}C$) carbon isotope ratios
mg/L	milligrams per liter
µg/L	micrograms per liter
bbl	barrels
BCF	billion cubic feet
MCF	thousand cubic feet
TCF	trillion cubic feet