SELECTED ANNOTATED REFERENCES ON WATER HANDLING, ENVIRONMENTAL, AND LAND-USE ASPECTS OF COALBED METHANE DEVELOPMENT

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INTRODUCTION

This selected group of 153 annotated references derives from a more comprehensive bibliography on the water handling, environmental, and land-use aspects of coalbed methane development (CBM) compiled by Western Ecological Services Ltd. for the B.C. Ministry of Energy and Mines (Peterson et al. 2002[*]). The main bibliography contains about 360 references presented in two formats: (i) a listing of all references in alphabetical order by senior author, with each reference described by five fields (Reference; Keyword phrases; Access for source document; Geographic location; Name of formation, coalfield or basin); and (ii) a separate listing of references sorted by 40 different keyword phrases.

From the main bibliography, references that contain the most substantial information about water handling, environmental, and land-use aspects of CBM development were selected for annotation of their subject matter content. Emphasis was given to concerns about CBM produced water and alternatives for handling this water. Approximately 42% of the references in the main bibliography were selected for annotating. For references not annotated, a reader can obtain information on their general content by referring to the keyword phrases under which each reference is coded in Peterson et al. (2002).

If a reader does not wish to consult all the annotations in this report, where is the best place to start? The references selected for annotation represent a broad range of vantage points: federal, state, and provincial agencies involved with CBM-related regulation, administration, or research; CBM developers and their technical and engineering support companies; landowners and public interest groups; professional associations; and academic research or extension groups interested in the CBM resource. Because annotations are listed alphabetically by senior author, there is no direct way for a reader to focus on references that represent a particular vantage point. It is also difficult to identify the most important references for the reader who, in the interests of time, might wish to read those annotations first. To identify certain references as the most important ones would be unfair to authors of the remaining references. However, it is suggested that for readers who want to begin with references that collectively provide a rapid overview of the broad range of subjects annotated, a good place to start would be the following ten annotations:

Rogers 1994 - for general principles and practices of CBM development;
Rice and Nuccio 2000 – for a concise scientific overview of the CBM resource;
Rice, Wanty, Byrer, and Kruger 1995 – for an overview of CBM development;
Lawrence 1993 – for a technical perspective from the CBM industry;
Shuey 1990 – for CBM regulatory and policy approaches;
Waren 1999 – for an agency approach to hydrologic monitoring;

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[*] Peterson, N.M.; Peterson, E.B.; Chan, Y.-H. 2002. Bibliography on water handling, environmental, and land-use aspects of coalbed methane development. Prep. for B.C. Min. Energy & Mines, Victoria, B.C.

O'Neil 1994 – for water quality monitoring of discharged CBM water;
Triolo, Ogbe, and Lawal 2000 – for CBM operations in cold regions;
Zander 1999 – for scoping of CBM environmental impact assessments;
East of Huajatolla Citizens Alliance 2001 – for public interest CBM concerns.

The annotations in this review are not a substitute for the details contained in original documents. For more detail, the interested reader should consult original source documents as identified in the main bibliography. This is particularly true for informative reports such as: ALL [Arthur Langhus Lane] Consulting and CH2M Hill (2001, two reports); Arthur et al. (2001); Davidson et al. (1995); Horn (1990); Lawrence (1993); Morrison et al. (2001); O'Neil (1994); O'Neil et al. (1993); Regele and Stark (2000); Rogers (1994); Schneider (2001); Society of Petroleum Engineers (1992); Warrance and Bauder (2001, two reports); and Wyoming Outdoor Council and Powder River Basin Resource Council (2001).

In addition to the references highlighted above, for which annotations could not capture the detail of original articles, there is a further category of important references that were not annotated at all. This category involves four kinds of references:

1. Two Powder River Basin environmental impact statement (EIS) reports are so detailed and comprehensive that credible annotation is not possible. These two EIS reports (both in draft status when posted to websites in January 2002) are:

   U.S. Bureau of Land Management, Montana Board of Oil and Gas Conservation, and Montana Department of Environmental Quality. 2002. Montana statewide draft oil and gas environmental impact statement and amendment of the Powder River and Billings resource management plans. Various paging. http://www.deq.state.mt.us/coalbedmethane/DraftEIS/DraftPublicEIS.pdf.

   U.S. Bureau of Land Management, Wyoming. 2002. Draft environmental impact statement and draft planning amendment for the Powder River Basin oil and gas project. BLM, Buffalo Field Office, WY. WY-070-02-065. Various paging. http://www.prb-eis.org/

2. There was also omission of some successive articles from one program or by one author that would be repetitive if all were annotated. For example, in the master bibliography (Peterson et al. 2002) there are a large number of references by O'Neil and co-workers on stream monitoring in relation to CBM produced water discharge in Alabama. Only two representative articles by O'Neil and co-authors are annotated. This limited selection of the excellent long-term biomonitoring of CBM water discharge in Alabama is not intended to lessen the importance of that series of studies. In the words of O'Neil et al. (1991, Geological Survey of Alabama Bulletin 141) "This study represents the most complete database compiled to date concerning the long-term effects of a coalbed methane produced water discharge on aquatic ecosystems."

3. The master bibliography lists many references that give information on how United States federal and state agencies regulate and administer water handling, environmental, and land-use aspects of CBM development. A few representative examples are annotated for this kind of information but most are not annotated, for two reasons: many documents of a regulatory nature are too detailed to annotate concisely and accurately; and in many cases the policies, administrative procedures, and regulations of other jurisdictions may not be applicable to British Columbia. Table 1 lists most of these un-annotated reports, by author (agency name) and title. The interested reader can view most of the Table 1 information sources on websites identified for these references in the master bibliography (Peterson et al. 2002).
4. Another group of references that were not annotated are generic descriptions of practices that do not specifically refer to CBM operations but may be applicable to such operations. The following references are examples of this category.

Author (Agency)*	**Report Title**
Bauder, J. 1998.	When is water good enough for livestock?
Bradley, R. 1993.	Design considerations for reverse osmosis systems.
Canadian Association of Petroleum Producers. 2001.	Produced water waste management.
Canadian Petroleum Association. 1990.	Production waste management handbook for the Alberta petroleum industry.
Colorado Oil and Gas Conservation Commission. 2001.	Exploration and production (E & P) waste management.
Colorado Oil and Gas Conservation Commission. 2001.	Sensitive area identification guidance document.
Davis, L. 1995.	A handbook of constructed wetlands – a guide to creating wetlands for agricultural waste, wastewater, domestic wastewater, coal mine drainage, stormwater in the Mid-Atlantic Region. Vol.1. General considerations.
Ground Water Protection Council. n.d.	Injection wells: an introduction to their use, operation, and regulation.
Ground Water Protection Council. 1995.	Injection well bibliography, 3rd ed.
Levelton [B.H.] & Assoc.; Talisman Land Resource Consultants; Hicks, A.M.; McDaniel's Research Ltd. 1991.	An inventory and analysis of control measures for methane for British Columbia.
Ray, J.P.; Engelhardt, F.R., editors. 1992	Produced water: technological/environmental issues and solutions.
Reed, M.; Jonsen, S., editors. 1996.	Produced water 2: environmental issues and mitigation technologies.
Santos, S.M.; Wiesner, M.R. 1997.	Ultrafiltration of water generated in oil and gas production.
U.S. Environmental Protection Agency, Office of Water. 1998.	Ground water protection programs.

* See Peterson et al. (2002) for complete citations.

TABLE 1. References from other jurisdictions on policies, administrative procedures, or regulations for CBM development that are not annotated in this report. See master bibliography (Peterson et al. 2002) for full citations of these references, many of which are accessible by website.

Author (Agency)	Report Title
Alabama State Oil and Gas Board. 2001.	State Oil and Gas Board of Alabama Administrative Code, Oil and Gas Report. Rules and regulations governing the conservation of oil and gas in Alabama and oil and gas statutes of Alabama with Oil and Gas Board forms.
Beach, G. 2001.	Discharges from off-channel, complete containment ponds.
Beach, G. 2001.	Interim guidance on permit applications for the Powder and Little Powder river drainages.
Beach, G. 2001.	Updated permitting options for coal bed methane permit applications.
Beach, G. 2001.	Use of CBM produced water for dust control on county roads.
Montana Environmental Quality Council, Coal Bed Methane & Water Policy Subcommittee. 2001.	Coal bed methane legislation – approved 2001 Montana Legislature.
Montana Environmental Quality Council, Coal Bed Methane & Water Policy Subcommittee. 2001.	2001-2002 Work Plan [of Coal Bed Methane & Water Policy Subcommittee].
Montana Department of Environmental Quality and Wyoming Department of Environmental Quality. 2001.	Montana and Wyoming Powder River interim water quality criteria memorandum of cooperation.
U.S. Bureau of Land Management, Montana State Office. 2000.	Draft planning criteria for the oil and gas environmental impact statement and amendment of the Billings and Powder River resource management plans, Miles City, Montana.
U.S. Bureau of Land Management, Wyoming. 2000.	Coal bed methane well application for permit to drill and project plan of development preparation guide.
U.S. Bureau of Land Management, Wyoming State Office. 2000.	Wyodak drainage coal bed methane environmental assessment (WY-070-01-034).
U.S. Bureau of Land Management, Wyoming State Office. 2001.	Decision record, Wyodak drainage coal bed methane environmental assessment (WY-070-01-034).
U.S. Congress, Senate Committee on Appropriations, Subcommittee on the Department of the Interior and Related Agencies. 2001.	Coalbed methane development in Montana, hearing before a subcommittee. U.S. Senate, 107th. Congress, First Session, March 10, 2001, Billings, Montana.
U.S. Environmental Protection Agency. 2001.	Underground injection control: Request for information of ground water contamination incidents believed to be due to hydraulic fracturing of coalbed methane wells: Notice.
West Virginia Bureau of Environment. 2001.	Coalbed methane wells rule.

Table 1. Continued.

Wyoming Department of Environmental Quality, Water Quality Division. 2000.	Coalbed methane NPDES (surface discharge) permits.
Wyoming Department of Environmental Quality, Land Quality Division. 2000.	Guidelines and standard operating procedures. Guideline 8. Hydrology.
Wyoming Department of Environmental Quality, Water Quality Division. 2000.	Antidegradation review, analysis and findings: concentrations of barium in the surface waters in northeastern Wyoming related to discharges of coal bed methane produced water.
Wyoming Department of Environmental Quality, Water Quality Division. 2001.	Analysis of comments [relative to "Draft antidegradation review, analysis and findings for concentrations of barium in the surface waters in northeastern Wyoming related to discharges of coal bed methane produced water"].
Wyoming Department of Environmental Quality, Water Quality Division. 2001.	Effluent limitation guidelines.
Wyoming Department of Environmental Quality, Water Quality Division. 2001	National Pollutant Discharge Elimination System, permit modification application for coal bed methane.
Wyoming Department of Environmental Quality, Water Quality Division. 2001.	National Pollutant Discharge Elimination System application for permit to discharge produced water.
Wyoming Department of Environmental Quality, Water Quality Division. 2001.	National Pollutant Discharge Elimination System application for permit to discharge produced water. Application short form C (v.2) for coal bed methane new applications or renewals.

In the annotations that follow, infrequently used abbreviations are defined in context. Some of the most commonly used abbreviations, not always defined within the annotations, are:

BLM	Bureau of Land Management
EPA	Environmental Protection Agency
CBM	coalbed methane
GRI	Gas Research Institute (which became GTI)
GTI	Gas Technology Institute
NPDES	National Pollutant Discharge Elimination System
SAR	sodium adsorption ratio
TDS	total dissolved solids
USDA	United States Department of Agriculture
USGS	United States Geological Survey

ANNOTATED REFERENCES

Alberta Department of Energy. 2001. [Tenure issues re: Coalbed Methane.] Feedback from Canadian Association of Petroleum Landmen and Canadian Association of Land Administration Round Table regarding May 24, 2001 Alberta P&NG Tenure Information Exchange. Edmonton, AB. 17 p.

A posting temporarily on the website (www.energy.gov.ab.ca) summarized an information exchange about potential CBM development in Alberta. This exchange indicated the need to consider CBM development in the context of surface disturbances and environmental issues such as water handling. There was a call for government and industry to share information on CBM development as it is a new land-use issue.

Alberta Energy and Utilities Board. 1991. Coalbed methane regulation. AEUB, Calgary, AB. Informational Letter IL 91-11. 6 p.

This 1991 Informational Letter proposed that a task group be established to monitor CBM development and recommend appropriate regulatory policies based on Alberta information. The Energy Resources Conservation Board (ERCB) and Alberta Department of Energy (Energy) consider coalbed methane to be a form of natural gas. As a result, all acts and regulations administered by ERCB and Energy that pertain to natural gas also pertain to coalbed methane. This letter indicated that:

- As with drilling under Oil and Gas Conservation Regulations, CBM operators will be "required to address all environmental and social impacts, and to address objections of directly and adversely affected persons. In particular, handling and disposal of the expected water production and possibly coal-fines need to be carefully planned, and appropriate approvals for disposal schemes obtained. Options for water disposal include treatment and release to the watershed, or subsurface disposal to a compatible formation".
- "Normal gas well spacing of one well per section applies, unless a change is approved under the Oil and Gas Conservation Regulations, Section 4.030. The effects on gas recovery, equity, and surface impacts will be considered in any change."
- "The impact that coal seam dewatering may have on area ground water aquifers must be addressed before large scale water withdrawals commence from any coal seam. If the produced water is potable, there is a possibility that Ground Water Removal Permits may be required by the Department of Environment under the Ground Water Development Act and the Water Resources Act."

Alberta Research Council. 1997. ARC investigates methods to reduce CO_2 emissions. Alberta Res. Council, Edmonton, AB. R&D, Summer 1997, p. 2.

The concept behind this Alberta Research Council study is to inject CO_2 into Alberta coalbeds to encourage methane release. The methane would be used to produce energy at power plants, and the CO_2 from methane combustion would be pumped back into the coalbeds to release more methane. During a 'proof of concept' study, scientists determined that some Alberta coalbeds can store large volumes of CO_2 – up to three times more CO_2 than methane under the same conditions. Seven groups funded phase one of this project: EPCOR, Environment Canada, Alberta Energy, TransAlta Utilities Corporation, Air Liquide Canada, Mobil Oil Canada, and PetroCanada Resources. This Alberta project, while still in an early stage, is similar to the well-established practice of using CO_2 injection to enhance production from oil wells.

ALL [Arthur Langhus Layne] Consulting and CH2M Hill. 2001. Water resources technical report, Montana statewide oil and gas environmental impact statement and amendment of the Powder River and Billings resource management plans. USDI, BLM, Miles City, MT. 53 p.

The points below list only the highlights of this detailed technical report. The interested reader can view the entire report on the website (www.deq.state.mt.us/coalbedmethane/index.asp, see Environmental Impact Statement).

This report begins with a review of the following water issues raised through a public scoping process during preparation of Montana's CBM Environmental Impact Statement:

- Groundwater quality and quantity – Comments suggested that CBM pumping would degrade water quality, cause cumulative groundwater impacts, deplete the quantity of groundwater, and cause groundwater aquifers to be contaminated from either boreholes or saltwater pumped from the ground.
- Surface water quality and availability – Concerns centred on the cumulative long-term effect of discharge of CBM water, CBM discharge coming from Wyoming into Montana surface waters, and concerns about wasting groundwater as a resource.
- Wastewater disposal and discharge – Concerns included siltation of rivers from increased flow, treatment of discharged water, landowners input into decisions about discharge on their land, questions about injection of discharged water, and suitability of discharged water for agricultural and livestock uses.
- Water conservation – Topics covered aquifer drawdown and recharge, water replacement cost, permitting questions, and wasting of water resources. The two main concerns were that water recovery wells will go dry due to lowered water tables as a result of CBM development, and aquifer recharge rates will be affected. There was particular interest about the fate of private water wells under the influence of CBM development.
- Water rights – Questions arose on the CBM use of groundwater without obtaining the rights to produce the water.
- Groundwater resource assessment – Many comments recommended preparation of a groundwater resource assessment and the need to gather baseline data on all groundwater resources prior to CBM development.

In a region that receives 40 cm or less precipitation each year, Montana residents were particularly concerned about impacts on local water balances. Assuming an average life of 20 years, a single CBM well could produce as much as 105 million gallons of water. In a development scenario of up to 26,000 CBM wells, the total volume of water produced from CBM wells in Montana could exceed 3 trillion gallons of groundwater. This raises concerns that are distinct from the issues associated with conventional oil and gas development. This technical report emphasizes use of existing water-related information in the context of: hydrologic setting and framework; hydrology regime; coal seam reservoir parameters and regional variations; faulting and fracturing relative to CBM development; artificial penetrations; groundwater and surface water interaction; groundwater production and usage by aquifer and by area; water quality characterization and impacts.

Some additional water-related issues identified are as follows:

- Coal aquifers are of special interest since they hold the CBM resource and production of methane will directly impact these aquifers. CBM production may also impact alluvium aquifers where they intersect coal seams. The most important groundwater-surface water interaction is the exchange of water between coal seams and surface water via alluvium. In Montana, several bands of coal seams outcrop as clinker in the watersheds of major streams. These clinkers give rise to springs that feed into rivers and alluvium. At times of little runoff, streams are particularly influenced by surface recharge from low quality coal aquifer water.
- Artificial penetrations include geotechnical boreholes, unplugged oil and gas wells, seismic shot holes, or open water wells that can conduct water from the surface into aquifers or between aquifers. A penetration open to an aquifer and to the surface can allow low quality CBM water deposited on the surface to enter the aquifer. A penetration open to more than one aquifer can allow water to flow between the aquifers and if one of the aquifers is being produced for CBM, the coal seam could act as a sink, drawing water from the other open aquifer. Artificial penetrations are a difficult threat to gauge because isolated water wells or boreholes can occur anywhere.
- Drawdown of coal seam aquifers is an unavoidable impact because the depressurization of coal seams is inherent to CBM production. During drawdown of coal aquifers, water wells near to but outside of a producing CBM field may also be influenced adversely. Drawdown can be documented with dedicated monitoring wells or by gauging private water wells.
- It is important to recognize that CBM operations may continue for 15-20 years in any given field. The combination of extraction rates and duration may cause groundwater drawdown for several miles from CBM operations.
- Groundwater drawdown can result in methane migration phenomena under adjacent leases, including methane liberation into nearby water wells. The San Juan Basin has experienced gas seeps and coal fires that appear to be increasing with increasing CBM production. It is hypothesized that lowering the water table in a monocline by downdip dewatering of coalbeds could allow CBM to desorb from the coalbeds. The desorbed gas could then migrate updip to surface seeps. Details of this process are not well understood.
- Impacts to surface water from discharge of CBM water can be severe depending on the quality of CBM water. Some watersheds may be able to absorb the discharged water while others would be sensitive to large amounts of low quality CBM water.
- This technical report states that CBM production in the Montana portion of the Powder River Basin will certainly impact groundwater. However, impacts to groundwater can be mitigated through use of water well agreements, limits placed on

discharge, and monitoring programs. Water rights and mitigation agreements can be used to protect groundwater wells and springs.
- CBM water production will vary considerably in volume and quality, and must be effectively managed during development. The following are typical produced water management alternatives used in other CBM basins: discharge to impoundments; discharge to surface water; disposal to shallow aquifers; disposal into deep zones; industrial beneficial uses; agricultural beneficial uses; and pre-disposal treatment.

This report on Montana's portion of the Powder River Basin concluded that:
- Methane cannot be produced unless the water level in coalbeds is pumped down. If these coalbeds are also the source for water in nearby wells, water levels in the nearby water wells may also be drawn down.
- Many water wells in Montana's portion of the basin are in shallow alluvial aquifers and deeper Cretaceous sands, and these aquifers would likely be isolated from impact by CBM development.
- Quality of CBM water is extremely variable and must be evaluated before discharge is permitted. Some coalbeds in the basin contain high quality water that can be used for livestock or irrigation. Water management alternatives will be driven by produced water quality.
- Water well and spring mitigation agreements will aid responsible CBM development while protecting water rights. As coal aquifer water levels are drawn down methane will be liberated. Methane could appear in local water wells and monitoring wells adjacent to CBM production.
- The groundwater volume in coals of the Powder River Basin is sufficiently large that full CBM development will not likely exhaust the groundwater resource. However, there could be adverse impacts such as some water wells becoming dry, reduced flow from springs, seeps from unlined impoundments, impact to soils irrigated with CBM water, and degradation of surface water quality.

ALL [Arthur Langhus Layne] Consulting and CH2M Hill. 2001. Soils technical report, Montana statewide oil and gas environmental impact statement and amendment of the Powder River and Billings Resource Management Plans. USDI, BLM, Miles City, MT. 1 vol. (various paging).

The points below list only the highlights of this detailed review. The interested reader can view the entire report on the website (www.deq.state.mt.us/coalbedmethane/index.asp, see Environmental Impact Statement).
- This Technical Report is an appendage to the Montana Statewide Oil and Gas Environmental Impact Statement and Amendment of the Powder River and Billings Resource Management Plans scheduled for release in 2001. In the reasonable foreseeable development for Montana, BLM estimates that there may be 10,000 to 26,000 CBM wells statewide in the next 20 years.
- It is known that CBM water is typically of lower quality than surface water or other groundwater. When considering the impacts of CBM water it is necessary to characterize the water itself, soils on which the water will be applied, and crops for which the water may be used.

- This report summarizes chemical constituents of CBM-produced water from Montana and Wyoming samples. Too detailed to annotate here, the report characterizes CBM water according to lowest, mean, median, and highest recorded concentrations of over 25 constituents.
- Based on the generally fine texture of surface soils (clayey) much of the soil in southeastern Montana will likely be susceptible to increasing sodicity when irrigated with water having a high sodium adsorption ratio (SAR). Actual irrigability of soils using CBM-produced water, especially those on higher terraces above stream valleys, needs to be determined on a site-specific basis. Risks of using water with high salinity or SAR for crop irrigation are reduction in crop yields and damage to soils structure.
- Other potential impacts from using CBM water can occur from land spreading and surface discharge of produced water into drainage ways. Impacts of these practices would include discharge of salts to the groundwater and accumulation of salt on the surface. Also, erosion and sedimentation could occur from additional flow in drainage ways. Altered hydrology of drainages would likely affect native plant communities, levels of productivity, and would change terrestrial and riparian habitats. These influences could be positive in dry habitats but adverse in places where CBM water quality decreases productivity. Discharging CBM water into surface streams may be acceptable under some circumstances providing there are measures to minimize erosion and harm to riparian vegetation and aquatic habitats.
- Erosion must be controlled when disturbing land during construction of roads, pipelines, and other facilities necessary for CBM production. Also, care must be taken to avoid introduction of noxious weeds.
- Certain trace elements in drinking water can be toxic to livestock. A comparison of water quality guidelines for livestock with expected average concentrations in Montana's CBM produced water indicates that such water would be satisfactory to excellent for use as livestock drinking water.
- Long-term land spreading of CBM water could lead to changes in native vegetation by increased abundance of salt tolerant plant communities with subsequent influences on wildlife habitat. Also, evaporated salts could accumulate in closed depressions, destroying vegetation in these low areas.
- Use of high salinity/high SAR CBM water may have long-term effects on crops. More salt tolerant crops such as barley and sugar beets, and hays such as Bermuda, wheatgrass, and wildrye may have to be grown where high salinity irrigation water is used, instead of the more salt-sensitive crops like wheat, alfalfa, corn, and clover.
- Changes may be required in irrigation management techniques when CBM water is used. Additional irrigation water will be needed for leaching to ensure salts are moved out of the rooting zone.
- The cumulative effects of the application of high SAR water involve changes to the physical characteristics of soil. For example, when soil is saturated with sodic water it disperses (deflocculates), leading to a shutdown of water and gas exchange processes in the soil. Because of their lack of structure, and general lack of vegetation, dispersed soils are very susceptible to erosion.

Applied Hydrology Associates, Inc. 1999. Coal bed methane. Applied Hydrology Associates, Inc. 3 p.

Applied Hydrology Associates, Inc. provides hydrologic consulting services for existing and proposed CBM projects. The company has performed transient groundwater flow modeling of the Powder River Basin to determine cumulative impacts of surface mining and CBM development of the Wyodak-Anderson Coalbeds, as well as groundwater modeling of the Ferron Sandstone Coal aquifer in the Uinta Basin to project cumulative impacts of 870 operating CBM wells on the groundwater system over the next 40 years. Other projects include: surface water and groundwater sampling as part of a water chemistry evaluation and compliance program in the Raton Basin; independent field audits of water disposal pits to evaluate water disposal options; data collection in the San Juan Basin through a series of nested groundwater monitoring wells; geology and hydrogeology characterization and impact evaluation for an environmental impact statement in the Piceance Basin; assisting CBM operators to obtain permits for surface discharge of produced water including interpretation of discharge rates, channel transmission losses, background chemical concentrations, test evaluations, and instream aquatic investigations.

Argonne National Laboratory. 2000. Produced water treatment and management. Argonne Nat. Lab., U.S. Dept. Energy, Argonne, IL. 2 p. Doc. 557-001.

It is estimated that 340 million barrels of produced water were generated in the United States in 1990 from non-associated gas and CBM production. Because of the large volume of produced water, the cost of its management has a strong impact on profitability in the industry, and in some cases regulation of produced water can shut down operations. About 60% of produced water in the United States is disposed through deep well injection at a cost of $0.50 to $1.75 per barrel in wells that cost $400,000 to $3,000,000 to install. Researchers at Argonne National Laboratory have been using a new membrane technology called electrodialysis, which is an electric-field driven process that uses ion exchange membranes for salt removal or concentration of salts. This method is able to produce more highly concentrated brine (up to 20%) and is relatively unsusceptible to fouling problems.

Arthur, J.D.; Langhus, B.; Epperly, D.; Bohm, B.; Richmond, T.; Halvorson, J. 2001. Coal bed methane in the Powder River Basin. *In* Proc., 2001 Ground Water Protection Council Annual Forum, Sept. 22-26, 2001, Reno, NV. 37 p. (unnumbered)

This article contains substantial detail on the impacts of CBM development with emphasis on soil, agriculture, and water resources. Potential reasonable foreseeable development in the Montana portion of the Powder River Basin estimates 26,000 CBM wells in the next 20 years. It is expected that about 10% of these wells will be dry holes. The first exploration wells in the Montana portion of this basin were drilled in 1990 and CBM has been produced since April 1999. To date, operations have used fresh water drilling fluids to protect the aquifers and the coal being drilled. Water supply for drilling is most often from produced water although ponds are also used for drilling fluids. CBM wells have not been artificially fractured although this technique may be used in some parts of the basin in the future. Produced water is piped away from the well site and is managed in several ways. Discharge permits require that produced water be discharged via pipeline rather than ditch so that suspended sediments are not incorporated into receiving waters. Some produced water is currently delivered to unlined ponds to supply water for livestock and wildlife. This article presents a 20-year water production decline analysis, although the actual average water production rates for individual CBM wells varied by location, coal seam thickness, coal reservoir properties, and well completion type.

This article gives most attention to water resource impact issues, although other areas of interest identified during public scoping also included concerns about air quality, soil, cultural and paleontological resources, geologic and mineral resources, agricultural resources, recreation areas, visual resources, wilderness areas, and land uses. Drawdown of coal seam aquifers is an unavoidable impact. Drawdown can be documented with dedicated monitoring wells or by gauging private water wells. Groundwater drawdown can result in methane migration between adjacent leases including methane liberation into nearby water wells. This article indicated the importance of estimating groundwater balance on a watershed basis.

Impact to surface water from discharge of CBM water can be severe depending on quality of the produced water. The largest impacts occur where CBM water is discharged into streams with low volumes and low sodium adsorption ratio values. Potential impacts of irrigating with CBM water are dependent on quality of the water. For the more saline sensitive crops, such as alfalfa, wheat, clover, and corn, salinity level of the average CBM water in the Powder River Basin is near the threshold that would cause yield reduction, and care is needed to ensure adequate leaching. More salt-tolerant crops, such as barley and sugar beets, as well as hays such as Bermuda, wheatgrass, and wild rye, may need to be selected where higher salinity CBM water is used for irrigation. Additional irrigation water is required for leaching salts out of the root zone. This increase in irrigation water may require agricultural producers to file for additional water rights.

The authors conclude that the impacts from CBM produced water can be mitigated through conservation, proper disposal methods, and beneficial uses of the water. The following are typical produced water management alternatives that have been effective: discharge to impoundments such as ponds or tanks; discharge to surface water, with discharge rates calculated on the basis of quality of the produced water and quantity and quality of the receiving water; disposal to shallow aquifers which has the advantage of preserving the CBM water resource at the same time that surface waters and soil are protected; disposal into deep zones which has the advantage of protecting surface water resources but the disadvantage that the CBM water resource may be lost; industrial beneficial uses such as coal mining which can require large volumes of water for dust control, slurry mining, and slurry pipelining, as well as other industries such as manufacturing or meat processing that may have uses for CBM produced water; agricultural beneficial uses to irrigate crops and to water livestock; and pre-disposal treatment, the economics of which varies on a site-by-site basis.

Bates, Jr., R.L.; McDaniel, R.; Luckianow, B. 1993. Chemical oxidation by H_2O_2 addition to satisfy wastewater oxygen demands during production field startup operations. *In* Proc 1993 International Coalbed Methane Symposium, May 17-21, 1993, Birmingham, AL. Univ. Alabama, Tuscaloosa, AL pp. 365-374.

CBM produced water systems typically do not provide for removal of organic pollutants. The produced water stream exhibits atypical high oxygen demands during initial pumping, apparently a result of the organic constituents of the fracturing fluids used in well development. In the Black Warrior Basin, Taurus Exploration, Inc., the largest CBM producer in this basin, modified its usual water treatment practices by feeding hydrogen peroxide as an oxidant to satisfy atypical oxygen demands. This paper evaluates performance of the system during the initial two weeks of oxidant feed.

- Biological oxygen demand (BOD) is defined as the quantity of oxygen used in the biochemical oxidation of organic matter in a specified time and at a specified temperature. By common usage the standard conditions for BOD analysis are taken as 5 days and 20° C. Standard conditions must be used in the analysis of BOD because the oxidation process resulting from microbiological activity is not instantaneous and proceeds over prolonged time periods, and also because microbiological activity rate is strongly temperature dependent.
- During 1990 Taurus experienced BOD exceedances of the NPDES discharge limits in existing produced water holding ponds. High BOD concentrations coincided with initial pumping from new CBM wells immediately following fracturing operations.
- Taurus assessed effectiveness of wastewater treatment in terms of: adequacy of oxygen being supplied by the hydrogen peroxide feed; effectiveness of the hydrogen peroxide feed in terms of utilization of the oxygen supplied; and effectiveness of the hydrogen peroxide feed in terms of reducing wastewater oxygen demand.
- Hydrogen peroxide feed was a very effective modification of the typical two-pond system to enhance system performance during CBM well startup. The oxidant feed should be started concurrently with initial pumping of CBM water. Also, pre-filling treatment ponds with water low in organic content will also help to avoid permit exceedances.

Bauder, J. 2000. Another one of those soil/water terms: SAR. Montana State University, Bozeman, MT. Agron. Note No. 250. 2 p.

Concerns about sodium in soil and water as a result of CBM operations dominated recent enquiries to soil specialists at Montana State University. In response, this extension note defines sodium adsorption rate (SAR) as an index to estimate the changeable sodium percentage of a soil or water. SAR has a good correlation to the exchangeable sodium percentage and is much easier to estimate. Exchangeable sodium in concentrations above 15% (or SAR = 13) exerts its greatest effect on plant growth by dispersing the soil. Colloid dispersal makes soil less permeable. The author describes the 'adjusted' SAR as a value corrected to account for removal of calcium and magnesium by their precipitation with bicarbonate or carbonate ions in the water added. This adjustment gives higher values for adjusted SAR than for SAR and is a truer picture of the sodicity of the soil or water. This means that in irrigation water that has calcium, magnesium, and sodium in the absence of carbonate or bicarbonate the magnesium and calcium can remain in solution and offset the effects of the sodium. However, in water that has a high concentration of carbonate and bicarbonate, along with calcium and magnesium (which is the typical case with CBM discharge water), the calcium and magnesium will precipitate as carbonates/bicarbonates when exposed to air. Thus, SAR calculated for water without accounting for the carbonate or bicarbonate content is a very conservative value. For a more accurate evaluation it is necessary to consider the presence of carbonates and bicarbonates and to use adjusted SAR.

Bauder, J.W. 2001. Quality and characteristics of saline and sodic water affect irrigation suitability. *In* Montana State University, Dept. of Land Resources and Environmental Sciences, Bozeman, MT. Water Quality and Irrigation Management, Position Pap. 6 p.

Sprinkler irrigation and land spreading are two alternatives for water spreading and achievement of beneficial uses for saline and sodic water. Extensive research has been completed in the Powder River watershed within the last decade to address impacts of the combined effects of both elevated electrical conductivity (EC) and elevated sodium adsorption ratio (SAR) in relation to CBM produced water. An interactive relationship between EC x SAR whereby the dispersive nature of sodicity is mediated is well known in the soil science literature. The author indicates CBM developers, consultants, and others interested in promoting CBM development are currently emphasizing this relationship. However, he cautions that sensitivity of the EC x SAR interactive effect to clay type, soil chemistry, and soil texture can reduce the meditative effect and will have significant adverse ramifications if overlooked during planning for disposal of saline/sodic CBM produced water.

Bauder, J. 2001. The role and potential of use of selected plants, plant communities, artificial, constructed, and natural wetlands in mitigation of impaired water for riparian zone remediation. *In* Montana State University, Dept. of Land Resources and Environmental Sciences, Bozeman, MT. Water Quality and Irrigation Management, Position Pap. 3 p.

Experience in Montana indicates that saline/sodic water, typical of some CBM produced water, often involves contact with soils that are calcareous and saturated with respect to calcium carbonate. Carbonaceous, calcic soil is a condition that will remain so when irrigated with saline/sodic water that is in chemical equilibrium with calcite. Under these circumstances irrigation of salt tolerant crops with non-saline water is the preferred method of reclamation but this is not likely an option in the CBM produced water discharge areas observed by the author.

Beattie, A.; Darin, T. 2001. Encouraging responsible coalbed methane development. Frontline Report (Wyoming Outdoor Council) Summer 2001:1-4.

The Wyoming Outdoor Council (WOC) is a public interest group with a goal of encouraging responsible CBM development. The group's "go-slow" CBM campaign focuses on the following points:

- In April 2001, American Rivers released its annual Most Endangered Rivers report, which listed the Powder River as the fifth most endangered river in the United States because of threats from CBM development.

- The Wyoming Department of Environmental Quality (WDEQ) recently announced its plan to revise three chapters of Wyoming's Water Quality Rules and Regulations. Among the suggested revisions, WDEQ has asked for input on whether landowners affected by CBM water discharges should receive targeted notification and whether effluent limits should be established on an industry-by-industry basis.
- WOC continues to file objections to CBM-related National Pollutant Discharge Elimination System permits, arguing for a moratorium on permits or at least a more cautious permitting approach. One objection is that WDEQ has not required CBM operators to obtain stormwater permits for their construction activities. Also, WDEQ has not required the CBM industry "to conduct toxicity testing of its discharge water even though studies show that salts may have toxic effects on aquatic species found in the Powder River Basin".
- The Underground Injection Control (UIC) program, a federal program under the Safe Drinking Water Act, protects underground drinking water sources from contamination by injected fluids. In May 2001, WDEQ held a public hearing to receive comments on its proposed UIC rule revision to facilitate reinjection of CBM water by altering the way it issues general permits for reinjecting fluids into specific aquifers. Before issuing such permits, WDEQ proposes to collect information on site-specific factors such as aquifer water quality, ability of the aquifer formation to receive reinjected fluids, and the possibility of cross contamination of aquifers. WOC cautions that reinjection is not a panacea, especially if it does not require treatment of produced water or require pre-injection separation of drilling fluids from CBM water.

Beckstrom, J.A.; Boyer, G. 1991. Aquifer protection considerations of coalbed methane development in the San Juan Basin. *In* Rocky Mountain Regional Mtg and Low-Permeability Reservoirs Symp., April, 1991, Denver, CO. Soc. Pet. Eng. pp. 371-386. SPE 21841.

Coalbed methane development in the San Juan Basin has caused concern about several environmental issues. This paper presents the findings of four groundwater sample programs, and describes aquifer protection work in relation to producing CBM wells. In some areas of the Fruitland Formation CBM wells produce over 1,000 barrels per day. Over time water production decreases and methane production increases. Produced water is gathered by pipeline systems or trucked to disposal wells or evaporation ponds. Most of the disposal wells in the basin inject the produced water into the Entrada or Morrison Formations (about 2743 m) that are separated from groundwater supplies by the Kirtland, Lewis, and Mancos Shales. Thus groundwater is protected from the produced water injected into the disposal wells by the shale sections overlying the injection zones, and also by use of fully cemented casings. Three large evaporation ponds are operated in the study area. All ponds are double lined and have leak detection systems. Two ponds also use sprinkler systems to accelerate evaporation. The sprinkler systems are not operated when winds are high enough to carry precipitation out of the holding ponds. Conclusions of the study emphasize the importance of water sampling techniques, the financial significance of aquifer protection, and the importance of information flow between industry, agencies, and the public.

Beckstrom, J.A.; Boyer, G. 1993. Aquifer-protection considerations of coalbed methane development in the San Juan Basin. SPE Formation Evaluation 8(1):71-79.

This paper presents the findings of four groundwater-sampling programs and other aquifer protection work on producing wells in the San Juan Basin. The study concluded that methane detected in domestic water wells near the Fruitland Coal Formation cannot be correlated directly with Fruitland CBM production.

Brady, L.; Cardott, B.J.; Schoeling, L.G.; Schrag, D.; Hump, K.; Skaggs, S. 1999. Coalbed methane development in the midcontinent area. Petrol. Tech. Transfer Council, Lawrence, KS. 3 p. Based on PTTC workshop, North Midcontinental Region, June 3, 1999, Wichita, KS.

This article highlights the following lessons learned from CBM developments in Kansas, Missouri, and Oklahoma:

- For a technically and economically successful CBM venture, the operator must have either a large proprietary acreage block or have cooperative agreements with other operators in a block;
- The quality of the gas must be assessed as well as proximity and operating pressure of pipelines to market;
- Cultural and natural features of the development area must be considered as well as environmental regulations;
- Suggested operating practices include: drilling a disposal well at the outset; selecting pumps as a function of needed sand protection; testing produced water to anticipate future scaling problems; and centralizing any needed compression facilities.

The authors note that although some Kansas coal seams can contain as much as 220 cubic feet of methane per ton of coal, not all of them are candidates for CBM production because they lack sufficient overburden or a competent shale seal. Despite these constraints, the Kansas coal area has the advantage of pipeline networks already in place and ample recognized zones for disposing of CBM produced water.

B.C. Ministry of Energy and Mines. 2001. Coalbed methane in British Columbia. Victoria, B.C. 10 p.

This brochure refers to the following water handling, environmental, and land-use aspects of CBM development in British Columbia:

- To encourage methane removal from coalbeds, natural pressures in coal seams must be decreased by dewatering the coal. Effective dewatering may take from several months to several years. The water is moved to a central discharge point, and depending on quality and quantity, is either injected back into the ground or used on the surface.
- CBM production must be continuous to ensure a constant gas flow and to sustain a commercially viable operation. If a CBM well is shut down for an extended period after it has started producing gas, water in the coal will collect at the well bore, requiring a repeat of the long dewatering process.

- Water is collected in storage tanks near the well and transported by truck to a disposal site or moved by pipeline to a suitable disposal site. Usually, to minimize surface impact, both gas and water pipelines are buried.
- Water production and disposal are key issues in CBM development. Drilling and production regulations require that water produced from natural gas operations, including CBM, be moved to an underground formation unless otherwise permitted. Groundwater is protected by lining drill holes with a casing and then cementing holes from production levels up to the surface. These procedures are designed to protect drinking water sources, fish habitat, and local vegetation.
- After rigorous testing, water that meets quality standards may be permitted to flow into surface drainages or into ponds from which it can seep back into the soil or evaporate naturally. The Oil and Gas Commission, in consultation with other departments, will review surface discharge options on a case-by-case basis.
- When the composition or volume of produced water makes surface disposal inappropriate, produced water is injected into deep wells. Water that tests high in total dissolved solids (including salts) is injected into suitable underground formations only after approval from the Oil and Gas Commission.
- CBM wells are subject to the spacing and target areas defined under the Petroleum and Natural Gas Act. Currently, British Columbia requires approximately 640 acres for each conventional natural gas well. However, United States experience indicates that CBM wells may need to be closer together than conventional gas wells.
- Producing CBM wells are relatively quiet, usually involving only small electric motors to pump water. The gas-powered compressors that move gas along transmission pipelines are equipped with strict sound-reduction systems. The effect of CBM development on wildlife occurs primarily from surface disturbances during construction of well sites and the pipeline network. To protect both domestic and wild animals, well sites are fenced and pipelines are buried underground where necessary. Once a well is depleted the operator is required to restore the area close to its original state.

Bumb, A.C.; McKee, C.R. 1984. Use of a computer model to design optimal well fields for dewatering coal seams for methane production. *In* Proc. Unconventional Gas Recovery Symp., May 13-15, 1984, Pittsburgh, PA. pp. 281-288. SPE/DOE/GRI 12859.

A model is presented for optimizing the number and locations of CBM wells for various hydrologic conditions. The model can handle confined or unconfined aquifers, leaky or non-leaky aquifers, isotropic or anisotropic permeabilities, existing wells at fixed or model-determined optimal flow rates, complex boundaries, and specified regions to be excluded from possible well-location sites for environmental or other reasons. Examples demonstrate that optimum CBM well field design differs significantly from the patterns widely used in the gas industry. Optimum patterns depend largely on reservoir and hydrologic characteristics of the target area, shape of the project site, existing wells, total number of wells, and water pressure drop in the coal seam required to initiate gas flow.

Burkett, W.C.; McDaniel, R.; Hall, W.L. 1991. The evaluation and implementation of a comprehensive production water management plan. *In* Univ. Alabama, Coll.

Cont. Studies & Coll. Engineering. Proc. 1991 Coalbed Methane Symp., May 13-16, 1991. Univ. Alabama, Tuscaloosa,

The authors, representing Taurus Exploration, Inc. and Dames & Moore, stressed that the management of production water is critical to successful CBM development. Many operators have initiated projects and made large investments but have then failed to move any gas to market because of water disposal problems. In the Black Warrior Basin, gas flow usually begins 1-10 days after dewatering has begun, although some wells require several months or even years to begin methane flow. Usually within the first month of a well's life, water production drops by as much as 70-90% of the initial rate before leveling off to a slow decline. The dewatering period is a function of the drilling pattern spacing. The larger the spacing between wells the longer the dewatering period.

Many factors affect quality of CBM produced water but of primary significance are the type and depth of coal seams. In general, produced water from deeper coal seams is more mineralized than water from shallow coals which are more likely to have hydraulic connections with less mineralized, shallow groundwater. Generally, CBM waters are technically not brines as occur with conventional gas reserves that contain over 35,000 mg/L TDS (total dissolved solids); in the Black Warrior Basin CBM produced water is slightly saline with concentrations of chloride ranging from 50-25,000 mg/L and iron ranging from 1-80 mg/L. The upper limits of chloride (25,000 mg/L) are found only in the deepest parts of the basin. Early 1980s water chemistry testing indicated that the only harmful constituents were iron, manganese, and TDS, the latter appearing mostly as sodium chloride. Therefore, the earliest permitting requirements in the Black Warrior Basin seemed straightforward – reduce the metals to allowable limits and establish a mixing zone for TDS that would protect aquatic organisms. Iron and manganese could be removed using treatment ponds in which produced water is aerated and oxidized iron and manganese would settle out in the water. However, TDS and chlorides are unaffected by aeration and the 1980s Alabama work focused on how TDS and chlorides influence aquatic species. Combining literature studies with field observations led the authors to conclude that the 250-mg/L standard limit for TDS was too restrictive, and Dames & Moore proposed a 500 mg/L upper limit for TDS concentration at the upper point of discharge. The Alabama Department of Environmental Management had set a limit of 190 mg/L for chlorides in streams that have less than 100 to 1 chloride dilution capability.

The authors emphasized the following points:

- The impact of flow multiplied by chloride levels is the controlling factor for discharging CBM produced water into surface waters.
- It is necessary to know the levels of iron in produced water to design settling and aeration ponds for removal of iron, and the same is true of manganese. In produced water, pH becomes a critical issue only when there are problems with iron and biological oxygen demand.
- In Alabama conditions, dissolved oxygen became critical only during the warmest months when water loses its ability to hold oxygen and releases it back to the atmosphere. If oxygen levels are less than 5.0 mg/L, aquatic life has problems.

- It is evident that CBM operators often must deal with complex water chemistry concerns. Use of qualified environmental personnel and laboratories is critical. The authors emphasized that it is cheaper for the operator to spend environmental dollars at the outset rather than trying to catch up to regulatory requirements.
- In Alabama, initially most operators made plans and applications on a worst-case scenario basis. A result was that assimilative capacities of almost all streams in the Black Warrior Basin were quickly exhausted by the permit assumptions. The Coalbed Methane Association of Alabama realized the inequities of the worst-case assumptions in the early permitting systems because it resulted in unnecessary restrictions on new companies wanting to pursue CBM development. The Association and the Alabama Department of Environmental Management developed a new and more realistic permitting system, details of which are provided in this article and in other Alabama references of this annotated bibliography.
- To evaluate a produced water management plan, an operator must consider five variables: production start-up schedule; flow rates per well; well flow rate variations over the life of the project; water quality; and stream assimilative capacity. These variables can change greatly during the life of a CBM project.
- Effective planning should consider the actual day-today variability in flow and not just statistical averages. This approach allows estimation of maximum storage requirements under different return period droughts, as well as under different CBM field development schedules. The end product is a prediction of storage requirement probabilities, and these data can be used to compare the costs of alternatives such as inter-basin produced water transfers, treatment of produced water, or well field shut-in.
- Initial planning before a project begins and refinement of the water management variables in that plan during development of a CBM prospect are critical to overall success of a project.

Byrnes, T.L.; Schuldhaus, K.F. 1995. Coalbed methane in Alberta. J. Can. Pet. Tech. 34(3):57-62.

In Alberta, early investigations into CBM production date back to the late 1970s but interest waned in the early 1980s with falling gas prices. More recent Alberta interest in CBM development was spurred by three factors: the large CBM resource potential in the province; the large amount of recent CBM activity in the United States; and environmental concern about CBM development in Alberta. Alberta's CBM resource is estimated to be comparable in size to the province's conventional natural gas resource base. Because CBM is a form of natural gas, it is regulated in the same manner as other natural gas. The authors, representing the Alberta Energy Resources Conservation Board (ERCB), elaborate on the application of natural gas regulations to CBM and also review some of the main regulatory issues that have arisen. They concluded that it is necessary to collect Alberta-specific CBM data before deciding whether there is a need for regulatory change specifically for CBM development.

At the time of this article, the authors indicated that the main concern expressed by the environmental community was the impact of CBM development on Alberta's natural areas. This was partly because many of the most promising coal areas are in the Rocky

Mountain foothills where there is public interest to maintain the natural state. This concern is heightened by the potentially closer than usual spacing of CBM wells and by the need to dispose of large volumes of produced water. The normal Alberta gas well spacing of 1 well per section (640 acres) was initially assumed to apply to CBM wells. As of 1995, the authors could draw no conclusion on the optimum well spacing for Alberta's CBM reservoirs. With regard to these concerns, the ERCB (now Alberta Energy and Utilities Board) and other Alberta regulatory agencies assumed that existing practices and policies related to conventional gas development would effectively handle CBM development. For example, increased well density would not be unique to CBM because in some circumstances, such as the shallow gas formations of southeast Alberta, conventional gas wells currently have a density of up to 4 wells per section. Also, thousands of oil and gas wells are already creating produced water in Alberta, with most of this water being injected into approved disposal wells. For these reasons the authors suggest that Alberta-specific data from some small-scale CBM projects were needed before deciding which, if any, regulatory changes are warranted for CBM development.

At the time of this article all gas production and water disposal facilities associated with CBM development were to be applied for and approved by the ERCB in the same manner as for other natural gas developments. Compositional analyses of produced gas and water samples from coal seams must be submitted to the ERCB in the same manner as those from other natural gas reservoirs. The impact that coal seam dewatering may have on groundwater aquifers had to be addressed before large scale water withdrawals could commence from any coal seam. If produced water is potable, a Ground Water Removal Permit could be required by the Alberta Department of Environmental Protection. In September 1991, ERCB initiated the Coalbed Methane Task Force, as proposed in Informational Letter IL 91-11. This group was formed due to public interest in CBM and consisted of representatives from environmental and land use groups, coal and gas industries, and various government agencies. The main objectives of the Task Group were: to monitor CBM development in Alberta; to recommend appropriate regulatory revisions regarding CBM development if needed; and to communicate factual information about CBM to interest groups and the public at large. As of 1995, the authors concluded that there was a need to get additional CBM information into the public domain to address outstanding concerns. At the same time, a reasonable period of confidentiality was recommended for certain CBM data to provide project proponents an opportunity to capitalize on their investments.

Cascade Earth Sciences (CES). 2001. CBM – produced water. CES handout at 2001 IPAMs Workshop. Albany, OR. 4 p.

Cascade Earth Sciences (CES) specializes in designing, building, operating, and financing land-based wastewater treatment systems, and is involved with field-scale tests to make beneficial use of CBM produced water in Wyoming. CES' conceptual approach for land-based management of produced water is based on a mix of technical and regulatory strategies:

- Iron and manganese levels in produced water are pre-treated using simple oxidation/precipitation techniques (aeration followed by settling in a pond);

- Soil and water conditioning amendments are used to mitigate sodicity, salinity, and alkalinity of the applied water to prevent reduction in soil infiltration capability and subsoil permeability.
- The overall goal is to provide beneficial use of produced water by increasing forage and plant community production. During the non-irrigation season CBM water is discharged in accordance with NPDES permits.
- Preliminary results indicate that the CES methods are cost effective. The approach developed by CES typically involves six tasks as listed below.
- Task 1 – Background review and site selection. This task selects the most appropriate location for the beneficial re-use system by assessing water flows, water chemistry, land topography, land ownership and use, presence of potable aquifers, and soil survey information.
- Task 2 – Conceptual design and flow process diagram. This step documents the type of land application equipment needed. A process flow diagram is developed.
- Task 3 – Site and soil characterization. This task characterizes morphological, chemical, and hydrologic properties of soils near the CBM production site. Soil scientists collect samples for analysis of cation exchange capacity, pH, sodium adsorption ration, electrical conductivity, lime content, organic matter content, and nutrients (N, P, K, S, B, Zn, Fe, Mn). The site's water holding capacity is also assessed.
- Task 4 – Crop and water management plan development. This plan includes: identification and management of limiting constraints for a 10-year site life; development of vegetation practices; recommendations for soil and vegetation improvements; controlling potential animal grazing; implementing runoff and erosion controls; and monitoring produced water flows, water quality, application rates, climate, crop performance, and soil quality.
- Task 5 – Final design and installation of the land application system. After completion of a detailed irrigation survey, a final design of the optimum land application system is prepared. The design is modular and easily moved to allow for flexibility in future water handling needs in the area.
- Task 6 – Startup and operation of the land application system. CES starts each system and operates it through completion of one operating cycle. At that time the operation can either be turned over to the CBM operator or CES can continue to operate the system depending on the needs of the client.

Case, J.C.; Edgar, T.V.; De Bruin, R.H. 2000. Subsidence potential related to water withdrawal in the Powder River Basin. Wyoming State Geol. Surv., Laramie, WY. 4 p.

Recent concerns have been raised about the potential of CBM water withdrawal to induce ground surface subsidence. In the United States the best-known locations where there has been ground surface subsidence related to fluid withdrawal are the San Joaquin Valley, Las Vegas, New Orleans, and Houston. The common geological feature of these sites is that all are underlain by saturated, unconsolidated sand and gravel with interbeds or overlying beds of saturated clay. Features of the Powder River Basin in relation to potential for subsidence are described as follows:

- Geologic conditions in the Powder River Basin are not the same as those in the cases cited above. Bedrock underlying the surface is compacted and consolidated; instead of loose sand, sandstone is present and instead of unconsolidated clay shale is present. If an aquifer is buried and overlain by relatively tight shale, the aquifer is labeled confined. If an aquifer is confined, water released from storage when the hydrostatic head declines comes primarily from compression of the aquifer, and to a minor extent, from expansion of the water.
- Coalbeds can also serve as aquifers. If the coal is buried, confined, and saturated it will also compress when water is removed. Some, but not all, water is pumped from coal beds to release methane in the Powder River Basin. If all the water were pumped from the coal, micropores in the coal would probably close which would stop most of the flow of methane through the coal. CBM producers try to keep enough water in the coal beds to prevent this from happening.
- In the Powder River Basin, because of the strength of materials above the coal, it is believed that only a minor part of any compression would be observed at the surface. The authors concluded that minor aquifer compression of up to ½ inch (1.3 cm) could occur. However, the entire compression may not be transmitted to the surface. Significant quantities of water have already been pumped from sandstone underlying the Wyodak Coal Zone. This water is used to supply Gillette, Wyoming, and to date no surface subsidence has been associated with this water withdrawal.

Coalbed Methane Coordination Coalition. 2001. Effective information transfer for rational development. CBMC Coalition, Buffalo, WY. 5 p.

This Coalition is composed of five county commissioners, two conservation districts, the state of Wyoming, and a representative of the CBM operators. Their activities include: presentation of CBM information to the public; landowner complaints; regulatory issues; streamlining processes for permitting and water handling; methods to optimize resource production and minimize negative impacts; setting baselines from which to monitor change; monitoring to assess change; developing mitigation measures when necessary; enhancing community resources; ensuring effective utilization of the water resource; develop issue papers on environment, health, and safety matters; and management procedures for CBM-related issues. The Coalition believes that regulation is not the first choice in problem solving, for several reasons: regulations represent a breakdown in collaboration and communication between stakeholders; regulations never end up as they start out; regulations eliminate flexibility in problem solving; a regulation subjected to litigation can delay implementation of a solution; and regulations, to be effective, need enforcement.

Coal Industry Advisory Board. 1994. Global methane and the coal industry: a two-part report on methane emissions from the coal industry and coalbed methane recovery and use. OECD/IEA, Paris. 67 p.

Current status of practices for CBM recovery in conjunction with coal mining operations is analyzed in this report. It draws on expertise and experience of coal industry operators who are routinely engaged in CBM recovery. An appendix of the report summarizes CBM recovery practices in Australia, China, Czech Republic, Germany, India, Poland, South Africa, United Kingdom, and United States. At present, in areas where coal is mined, the primary motivation for CBM recovery is mine safety. Economic conditions that support commercial CBM recovery in conjunction with coal mining are rare. The obstacles to expanding CBM recovery and utilization from coal mining areas vary from country to country. CBM recovery by surface drilling prior to mining is limited in some countries by environmental concerns as well as public resistance to expanded surface operations.

Vertical wells drilled into coal seams often produce only limited methane without stimulation. Therefore, stimulation through hydraulic fracturing is a common practice. Vertical wells typically intersect coal seams vertically. Although they can be drilled without interfering with mining operations, vertical wells produce gas at lower rates than horizontal boreholes drilled into the coal seam, which tend to be longer than the fractures created by fracturing from a vertical well. Thus, directional boreholes drilled from the surface and gradually deflected to intersect the coal seam horizontally can incorporate both advantages. However, industry has been frustrated in attempts to produce gas from such boreholes because of the high cost of drilling and difficulty of dewatering. The authors recommend further research on this subject.

In some coalfields, especially in the United Kingdom, coal seams are overlain by major aquifers, giving rise to concerns about flooding via CBM boreholes. The potentially divergent goals of coal extraction versus CBM utilization make it difficult to devise practical and sound public policy for developing the CBM resource in a coal mining area. Any solution must recognize that the methane in a minable seam of coal typically represents only a fraction of the total value of the coal.

Collerson, K.D.; Gregor, D.J.; McNaughton, D.; Baweja, A.S. 1991. Effect of coal dewatering and coal use on the water quality of the East Poplar River, Saskatchewan: a literature review. Environ. Can., Inland Waters Dir., Water Quality Div., Regina, SK. Sci. Ser. 177. 58 p.

This report does not deal specifically with CBM produced water, but it is a comprehensive literature review of water quality effects of coal dewatering in the Williston Basin. Both the Water Quality Branch of Canada's Inland Waters Directorate and the National Hydrology Research Institute conclude in this report that radionuclides and metals in the dewatering discharges are sufficiently low that they pose no immediate danger to the environment or to humans. This detailed review covers several topics potentially relevant to handling CBM produced water, including: hydrogeochemistry of surface water and groundwater; recharge to the water table; groundwater movement through aquifers; uranium geochemistry of groundwater; radionuclide behaviour and radiochemistry of coal and groundwater; and physical, chemical, and biotic properties of trace elements. An appendix lists maximum permissible concentrations in freshwater (United States criteria), mean natural concentrations in soil and in freshwater, degree of toxicity to various organisms, degree of bioaccumulation in fish and in food chains, and other key physical or chemical characteristics for each of 33 trace elements, some of which may be constituents of produced water.

Collett, T. 1997. Coalbed methane: an untapped energy resource and an environmental concern. U.S. Geological Survey, Energy Resour. Sur. Prog. Fact Sheet FS-019-97. 4 p.

Methane from coalbed reservoirs can be recovered economically but the disposal of water is an environmental concern. Water may be discharged on the surface if it is relatively fresh but often it is injected into formations at a depth where the quality of the injected water is less than that of the host rock. Another alternative is to evaporate produced water and collect the potentially saleable residues, an approach that might be feasible in regions with high evaporation rates. Contamination of aquifers due to CBM development is also an environmental concern. Studies by U.S. Geological Survey scientists indicate that there can be multiple sources of groundwater contamination: natural causes along fractures and from shallow biogenic gas; seepage from older deteriorating gas wells that had been completed in sandstone reservoirs; and from recently completed CBM wells. This suggests the importance of determining baseline conditions before large scale CBM development takes place. The author stressed that, since each coal-bearing basin has unique attributes, CBM issues need to be studied separately in each basin.

Cox, D.O. 1993. Coal-seam water production and disposal, San Juan Basin. Quart. Rev. Methane From Coal Seams Tech. 11(2):26-30.

Water disposal in the San Juan Basin is a significant long-term issue. Additional disposal wells or alternative treatment methods will be needed in the Colorado portion of the basin, where shortfalls in total injection capacity of the existing disposal wells and insufficient ultimate storage capacity of the deep Jurassic disposal horizons are indicated. At the time of this article, injection well problems were suspected. Preliminary analysis of 51 disposal wells showed 8 wells with injectivity declines. Disposal well operations must be monitored to determine long-term capacity, causes of declines in injectivity, and how these wells can be remediated. This article described work to: forecast CBM water production; characterize the disposal reservoirs; assess constraints to deep well injection; and analyze treatment technologies for surface discharge. A separate article (Stevens 1993) describes the water treatment aspects of this work.

These studies involve two key questions: Do existing disposal wells have the injection capacity to accept the projected rates? Do the disposal horizons have sufficient long-term storage capacity? The injection flow capacity of each disposal well was computed from the maximum injection pressure limitation imposed by regulatory agencies. By this procedure, the total injection capacity of all disposal wells within each designated area can be compared to the projected peak water production rate from that area. This analysis is based solely on the physical flow capacity of the wells. Other considerations, such as well ownership and regulatory requirements, could constrain drilling of additional disposal wells. Ultimate storage capacity of the disposal zones was estimated volumetrically. Because the deep horizons are already saturated in the San Juan Basin, storage is achieved by compressing the fluids and by expanding the pore space with higher pressure. According to the author’s computations, the deep disposal horizons in some parts of the San Juan Basin apparently have insufficient ultimate storage capacity to accept all the projected CBM produced water, but other areas apparently have no anticipated storage problems.

Cox, D.O.; Stevens, S.H.; Hill, G.D.; McBane, R.A. 1993. Water disposal from coalbed methane wells in the San Juan basin. *In* Proc. 68th Annu. Tech. Conf. & Exhibit. SPE, Oct. 3-8, 1993. pp. 131-140. SPE 26384.

Water produced from coalbed methane in the San Juan Basin presents a costly disposal problem and is viewed as a significant long-term issue. Currently, the main disposal method is underground injection. This is a concern because the volume of produced water expected in the decade after this article was written was expected to exceed the volumetric capacity of the deep disposal zones, implying that other disposal zones or other methods of handling produced water will be needed. The authors note that alternative treatment technologies are available for produced water to make it suitable for surface discharge. At the time of this article, deep injection of produced water cost about $1.00 per barrel. Reverse osmosis or electrodialysis was estimated to cost $0.30 to $0.70 per barrel. Besides the economic saving to operators much of the produced water could be made suitable for agricultural or municipal uses if treated by reverse osmosis or electrodialysis.

Crow, P. 1999. Fracturing fuss. Oil & Gas J. 97(35):37.

In August 1999, the Alabama Oil and Gas Board yielded to a court mandate requiring that fluids used to fracture coalbed methane reservoirs must meet the U.S. Environmental Protection Agency's primary drinking water standard. The case has implications for 12 other states in which there is CBM production. Opponents to the rules requiring fracturing fluids to meet the primary drinking water standard have pointed out that there has never been a confirmed case of pollution from underground fracturing of coal seams in the 13 states that have CBM production.

Darin, T. 2000. WOC protest halts coalbed methane discharge permits. Wyoming Outdoor Council Frontline Report Summer 2000. 2 p.

This website note explains how the Wyoming Outdoor Council and Powder River Basin Resource Council persuaded the Wyoming Department of Environmental Quality to defer decisions on 37 permits for discharge of CBM produced water until there is applicant demonstration that agricultural uses will not be impaired by release of water with high salt content. Another 43 discharge permits for CBM wells were also deferred until sodium adsorption rates (SAR) were re-evaluated according to 'adjusted' SAR (see annotated reference, Bauder 2000, Agronomy Note 250).

Darin, T. 2000. WOC pursues coalbed methane development reforms. Wyoming Outdoor Council Frontline Report Summer 2000. 7 p.

The public interest represented by the Wyoming Outdoor Council challenged what it considered to be undue BLM haste in approving CBM development. BLM contends that if there is not hasty action methane owned by the federal government will be lost, along with millions of dollars in royalties, as a result of CBM extraction on adjacent state and private lands. The Council criticized BLM and the CBM industry for preferring to evaluate small projects of 100-200 wells since the environmental impacts of small projects appear less than the total project impact of potentially 70,000 or more wells in that basin.

The Council lists several negative impacts of CBM development: added infrastructure requirements such as power lines and roads; water discharge concerns; aquifer depletion; undue surface disturbance and soil erosion; disturbance to the nation's last intact mixed grass prairie ecosystems, including weed infestation; impacts to vegetation, surface waters, fisheries, and wildlife; disruption of cultural, topographic, and aesthetic features; and loss of agricultural and recreational resources.

Darin, T. 2001. Coalbed methane update: 139,000 wells for the Powder River Basin? Wyoming Outdoor Council Frontline Report Fall 2001. 3 p.

When the Bureau of Land Management (BLM) announced its intent to prepare a draft environmental impact statement for the Powder River Basin in 2000, it first predicted a total of 30,000 CBM wells. Within months BLM revised the estimate to 51,000-70,000 wells. In January 2001 there were reports of potentially 120,000 wells in the Powder River Basin, based on estimates of the Powder River Energy Corporation of energy needed by submersible pumps and compressor stations in CBM operations. Some BLM estimates are as high as 139,000 CBM wells overall. There is a recently mandated 80-acre spacing for CBM wells but, depending on the assumed total area of development in the Powder River Basin, spacing of 139,000 wells could theoretically be as dense as 1 well per 25 acres.

Davidson, R.M.; Sloss, L.L.; Clarke, L.B. 1995. Coalbed methane extraction. IEA Coal Research, London, U.K. IEACR/76. 67 p.

This report contains an informative review of environmental aspects of CBM development, including treatment and disposal of produced water. The extensive literature review is international in scope, although most of the citations are based on United States CBM experience. The full report should be consulted as only the highlights are annotated below.

- The principal environmental considerations associated with CBM extraction are: environmental impacts of exploration, development, operation, and closure of a well field; disposal of water produced during well stimulation and methane production; and adverse effects on subsurface resources especially groundwater.
- Drilling CBM exploration wells can be arranged to minimize problems. The management of drilling fluids is the greatest environmental concern during this phase.
- In addition to drilling production wells, it is necessary to develop infrastructure such as gas and water collection lines, wellhead facilities, water treatment facilities, access roads, and equipment for processing and pumping gas.
- The largest surface disturbance associated with development of a CBM field is the drilling of wells, mainly because vegetation in the immediate vicinity of the well is destroyed.
- Many of the environmental concerns associated with CBM production centre on management of produced water.
- The amount of dewatering required can vary greatly between coalfields and between wells within an individual field. More water is produced from coalbed methane extraction than from natural gas extraction. On average, for wells in the United

States, coalbed methane produces about 1.74 cm^3 water per cubic metre of gas, compared to conventional (non-associated) natural gas yields of about 0.13 cm^3 water per cubic metre of gas.

- Many factors influence the quantity of water produced, of which the most important are the depth and age of the coal seam. Deeper coal seams, which are usually less permeable, generally produce smaller quantities of water compared to shallower seams. Production of water typically peaks in the early stage of pumping and then declines to a constant rate.
- Most wells require stimulation before methane production can begin. Stimulation may consist of pumping water and sand or other additives into the coal formation. Additives may include polymer surfactants, biocides, iron chelating agents, or other chemicals.
- Discharge of water containing high concentrations of total dissolved solids is considered a problem because of undesirable effects on aquatic organism and drinking water sources. Coalbed methane water generally has much lower concentrations of dissolved organic compounds compared with water from natural gas wells.
- Where concentrations of total dissolved solids and other contaminants are low, water may be suitable for direct discharge without treatment. In most cases, some form of water treatment is necessary, and current disposal practices include subsurface reinjection, discharge to surface waters, direct land application and surface evaporation, and advanced treatment systems.
- To design an effective system for treating or disposing produced water it is necessary to know the following: likely quality of produced water; estimated water production rates at various phases of the project; nature of any proposed receiving waters in terms of seasonal flow rates, existing water quality, and aquatic flora and fauna; and current or proposed permitting and regulatory restrictions.
- The main attributes preventing direct discharge of water are salinity (usually measured by total dissolved solids) and the possible toxic or ecological effects of certain inorganic ions and trace organic substances. The chloride concentration of water from CBM wells is often the parameter controlling discharge.
- Transfer or holding ponds may be necessary during periods when the flow rate of receiving waters is insufficient. Discharge to surface waters after aeration and settling has proved to be a cost-effective method for treating CBM produced water. In direct land application, water is usually moved via buried flow lines and applied by spray irrigation.
- Surface evaporation pits have been used for disposal of small quantities of water in regions with a climate suitable for high evaporation rates. There have been suggestions to propagate suitable species of salt-tolerant trees to hasten evapotranspiration of CBM produced water. Trees are probably suitable only with long term, centralized water storage systems because it takes many years for trees to reach maximum transpiration capacity.
- Membrane desalting processes, such as reverse osmosis, electrodialysis, and advanced evaporative methods, can be used to remove chlorides, iron, and manganese from produced water. Reverse osmosis produces a large volume of relatively clean water and a small amount of concentrated brine. This clean water is

generally suitable for discharge to watercourses or for application on the land. Because electrodialysis relies on conductivity of the water it is not possible to treat waters containing a low concentration of salts. Therefore, electrodialysis does not purify water to the same degree as reverse osmosis. Membrane fouling is a major limitation of both reverse osmosis and electrodialysis techniques. Evaporative processes, including surface boiling/condensing and flash evaporation systems, have also been used for desalination of water.

- It is prudent to carry out hydrologic studies in CBM fields to discover whether water removal will affect adjacent aquifers and to what extent this may be balanced by surface recharge.
- It is possible that when coal seams have been disturbed methane could seep through overlying strata to the surface. Methane can migrate upwards along natural faults and fractures or along other conduits such as boreholes. Groundwater can be contaminated by methane during such seeps.
- Most of the problems associated with CBM exploration and development can be overcome by careful planning followed by monitoring as the project progresses. The disposal of CBM produced water has proved to be the biggest environmental problem associated with coalbed methane fields in the United States. The authors note that it is unclear whether similar problems would accompany coalbed methane extraction in other regions.

Davis, H.A. 1993. Coalbed methane produced water management guide. Treatment and discharge to surface water: Black Warrior Basin, Alabama. Gas Research Inst., Chicago, IL. 183 p.

To assist management of CBM produced waters, the Gas Research Institute (GTI) in cooperation with the Coalbed Methane Association of Alabama developed a guidance manual that presented state-of-the-art methods for managing Black Warrior Basin produced water through use of treatment ponds and NPDES permits. Six different treatment pond systems were studied to develop the manual, which cover produced water characteristics, NPDES permit requirements, criteria for sample collection and testing, pond-based treatment methods, pond management, and process troubleshooting. Troubleshooting is discussed in terms of typical problems such as algae, pH, dissolved oxygen, and total suspended sediments with recommendations on visual observation of these problems and suggestions for corrective action. GTI member price for this manual is $35 (http://griweb.gastechnology/org).

Dawson, F.M. 1995. Coalbed methane: a comparison between Canada and the United States. Geol. Surv. Can., Ottawa, Ont. Bull. 489. 60 p.

Canadian CBM resources are undeveloped compared to the United States where coalbed methane has been produced since the mid 1970s. Exploration for coalbed methane in Canada began in the late 1980s with most activity in Nova Scotia, Alberta, and southeastern British Columbia. This paper summarizes the geological framework of the San Juan and Black Warrior Basins, the two main CBM-producing basins in the United States, and provides a comparative geological overview of potential CBM basins in Canada. The report does not review environmental aspects of CBM development; it focuses on geological criteria such as coal distribution, seam depth and thickness, petrographic characteristics, structural setting, and theoretical gas capacity. Some points made by the author that relate to environmental or land-use aspects are as follows.

- Factors such as coal quality and maceral composition, depth of reservoir, regional water table and reservoir pressures, permeability and fracturing, infrastructure availability, and drilling and completion costs all play major roles in determining the viability of CBM projects.
- Access and water disposal costs are sometimes greater than the cost of drilling a CBM well. One factor that makes the Fernie Basin attractive as a CBM target is proximity to the Westcoast Transmission Limited Pipeline to the United States.
- In contrast to the high infrastructure cost of the foothills and mountain regions, CBM exploration in the Alberta Plains has relied heavily on presence of existing oil and gas fields. Several companies have initiated projects to explore the feasibility of extracting coalbed methane from existing wells in the Mannville and Scollard Formations. Many of these wells are nearing the end of production from the conventional hydrocarbon pool. Rather than abandoning such wells companies are considering re-completing for coalbed methane. Some of the wells in the existing field may also be used for CBM water disposal.
- It can be surmised that in mountainous terrain CBM development may be concentrated at relatively low elevations because the author indicates that in such terrain the coal must lie below the regional water table (represented by the major river valleys) in order for the methane to be retained in the coal seam.

Dawson, F.M. 1999. Coalbed methane exploration in structurally complex terrain – a balance between tectonics and hydrogeology. *In* M. Mastalerz, M. Glikson, and S.D. Golding, editors. Coalbed Methane: Scientific, Environmental and Economic Evaluation. Kluwer Academic, Dordrecht, Neth. pp. 111-121.

CBM exploration in the Western Canada Sedimentary Basin has focused mainly on the foothills and mountain regions of Alberta and British Columbia because of the numerous thick coal seams of suitable rank for thermogenic gas generation. These regions are structurally complex and present unique challenges in defining and exploring for the optimum CBM exploration target. To delineate potential reservoir traps, it is necessary to understand the style of deformation and the main structural features where permeability enhancement may occur. The axial regions of anticlines and synclines appear to have the greatest potential. In general, the anticlinal structures occur in hanging walls of thrust faults and tend to form the mountain peaks. The synclines tend to lie within valley bottoms.

In addition to structural complexity, topography and local hydrogeology influence the depth of the reservoir, as well as subsequent reservoir pressure and gas retention within the coal seams. Gas desorption experiments in the Mist Mountain Formation of southeast British Columbia demonstrated that, in most cases, coals must lie below the regional water table, or be a sufficient distance from subcrop, to ensure that the adsorbed methane is retained within the seam. In synclinal structures, the dipping limbs can provide the hydrologic recharge and hydrostatic head to allow overpressured reservoir conditions to exist in the axis of the fold. The regional migration of gas downdip via the coal seam aquifer can also result in formation of biogenic methane that may enhance the resource potential. Structural trap examples from Canada and Australia indicate that permeability enhancement is required to achieve economic production from most CBM fields. An understanding of local hydrological conditions of the potential reservoir is critical to the producibility of the CBM reservoir in structurally complex terrain.

Dawson, F.M.; Marchioni, D.L.; Anderson, T.C.; McDougall, W.J. 2000. An assessment of coalbed methane exploration projects in Canada. Geol. Surv. Can. Bull. 549. 217 p.

The authors defined a set of key geological parameters necessary for successful CBM generation, storage, and producibility. One of the desired parameters was that there should be minimal remediation required for any produced waters. In some reservoirs, such as the Elk Valley of southeast British Columbia, water quality appears to be fresh so minimal remediation would be required for any produced waters. In the Tertiary Scollard/Upper Coalspur Formation in Alberta's shallow foreland basin, produced formation waters are also generally fresh. Similarly, in the Foothills and Mountain structural deposits, the Mist Mountain Formation of southeast British Columbia and southwest Alberta has fresh produced water, as does the Gates Formation. In contrast, in the Mannville Group of the Alberta Plains, produced waters are high in total dissolved solids and require special treatment and disposal techniques that add to production costs.

Aside from handling produced water, conflicting uses of surface land can be a concern. For example, the authors mention that the main detractor for CBM exploration and development in the Nanaimo coalfield is present land use. Much of the prospective area has undergone extensive urban development and there could be resistance to installation of numerous CBM production wells.

De Bruin, R.H.; Lyman, R.M.; Jones, R.W.; Cook, L.W. 2001. Coalbed methane in Wyoming. Wyoming State Geol. Surv., Laramie, WY. Inf. Pam. 7 (rev). 19 p.

Several frequently asked CBM questions are addressed by this information pamphlet, in which some of the highlights are:

- CBM operations can affect coal mining. For example, produced water discharged to the surface upstream from a mine could create water control problems not anticipated in the original mine plan. As a positive, dewatering and degassing the coal in advance of underground mining eliminates the methane hazard and lessens the amount of water that has to be pumped from the mine. In turn, coal mining can affect CBM recovery by removing the methane reservoir. Coal mining can also remove some of the water in coal near the mine, thus stimulating more free methane production as CBM operations approach the active mine areas.
- The possibility of either methane seeps or underground fires occurring as a result of CBM development is extremely remote. CBM production lowers both the pressure of gas in the coalbed and the hydrostatic pressure in adjacent aquifers, thus lessening the chance for gas seeps to develop.
- Although withdrawal of fluids from subsurface aquifers is known to cause subsidence in many areas of the world, measurements in Wyoming showed that compression due to dewatering of a coalbed in the Gillette area amounted to less

than 0.5 inch and only a minor part of the compression would be observed at the surface.
- Most CBM produced water in Wyoming is currently discharged into surface drainages, or is placed in ponds where it can seep back into soil or evaporate. Some produced water is being reinjected into the coalbed of origin or into nearby aquifers.
- Sodium adsorption ratio (SAR) is the ratio of the concentration of sodium to the combined concentration of calcium and magnesium. Since SAR is a ratio it is possible to have very low sodium levels yet high SAR values if there is near absence of calcium and magnesium in the water. High SAR values indicate potential agricultural problems. SAR values for Wyoming CBM water range from 3 to over 60. In general, clay-rich soils are more susceptible to damage from high SAR values than are sandy or loamy soils.
- In Wyoming, if produced water is of poor quality it cannot be discharged into drainages. Options are lined impoundments (evaporation ponds), chemical treatment, or reinjection into aquifers.
- Beneficial uses of CBM produced water include: livestock watering; field irrigation; direct use for human drinking water; supplementary source for municipal water; use in coal slurry pipelines; creation of new wetlands; creation of reservoirs for fish production; other recreational uses of water; and industrial uses such as cooling water for coal-fired power plants, coal gasification plants, and synfuel plants.
- Some water wells near CBM production areas can experience lowered water levels and gas seepage into the water. As a result, water regulatory officials encourage landowners to register their water wells so that if a well is damaged it can be remedied by the responsible CBM operator. Many landowners negotiating with CBM operators now sign letters of understanding which specify what will be done if their wells are damaged by CBM activities.
- Some studies have shown that certain aquifers are being recharged with water produced from CBM operations. However, it may take hundreds of years to fully recharge the coalbeds that have been dewatered for methane production. As deeper coal beds are tapped for methane in multiple coal zones, it may be possible to re-inject water from the deep coal beds into the gas-depleted shallow coal beds, thus accelerating the recharge process.
- Several factors will affect the projected growth of the CBM industry including: federal and regional planning and permitting procedures; development of technology allowing completion of multiple coal seams from a single well bore; interjurisdictional arrangement on how to handle water quality issues; and limitations imposed by infrastructure such as the requirement for adequate pipeline capacity to transport methane from the production areas.

DeWalle, D.R.; Galeone, D.G. 1990. One-time dormant season application of gas well brine on forest land. J. Environ. Qual. 19:288-295.

This article deals with produced water from a gas well in Pennsylvania. It is annotated only to demonstrate potential beneficial surface uses of saline produced water. Examples include road spreading for dust control, de-icing road aggregate storage piles, and surface application to forestland. The authors conclude that if toxic chemical constituents are removed, then one-time dormant season applications of brine to forest land, at rates of about 0.7 kg/m^2 or less of chloride, are feasible without vegetation damage. They suggest that larger scale and longer-term experiments are needed to assess overall applicability of forestland brine disposal under a variety of vegetation, soil, and brine conditions.

Drottar, K.R.; Mount, D.R.; Patti, S.J. 1989. Biomonitoring of coalbed methane produced water from the Cedar Cove degasification field, Alabama. *In* Proc. Univ. Alabama Coalbed Methane Symp., Tuscaloosa, AL. pp. 363-367.
To develop environmentally acceptable criteria for CBM water discharge, aquatic effects of these waters were evaluated using standard effluent biomonitoring tests. Produced water was not acutely toxic to rough shiners or fathead minnows, but was both acutely and chronically toxic to *Ceriodaphnia* sp. Toxicity characterization suggested that acute effects were caused by chloride concentrations. Assessment of chronic toxicity indicated that there was a second source of toxicity but it could not be identified. Because chloride tolerance varies widely among aquatic species and therefore among aquatic communities, site-specific evaluation of ecological susceptibility to high chloride concentrations may help define appropriate discharge levels of CBM produced water.

East of Huajatolla Citizens Alliance. 2001. Information sheets on coal bed methane development in the Raton Basin. Colorado. (http://ehcitizens.org/cbmgas/info_sheets.htm).
The web site for this public interest group presently contains 38 two-page Information Sheets, of which the eleven annotated below deal most directly with water handling, environmental, and land-use aspects of CBM development.

- Information Sheet #2, Produced water. In 1998, for 435 active CBM wells in Las Animas County, on average each CBM well was producing enough water for four families to use for a year. The approved methods of disposal were: reinjection, evaporation/percolation pits, approved commercial facilities, road spreading, and discharge to state waters. Regarding beneficial use of water, there is a legal concern in Colorado. When water is put to a beneficial use as defined by state law, then the user can file for a water right. The process can be complicated and there is a question whether the produced water is already owned by someone or is it 'new' water to be claimed. These complications cause most CBM producers to dispose of the water rather than offer it for beneficial use. Two different methods of water quality testing are applied to CBM produced water. The first method tests for individual contaminants and is used in baseline water quality testing of domestic wells and surface waters. The other method is more general and takes into account cumulative effects of individual contaminants. Discharge permits for CBM produced water require testing by both methods. While it is generally true that CBM wells are drilled to depths below domestic water wells, some residents in this area have been informed that they will lose their domestic water wells when the methane is fully extracted.
- Information Sheet #3, Biography of a coal bed methane field. A CBM field can produce gas for 15-30 years. During that period, there is a progression of events with most activity occurring at the beginning. This article outlines the progression of steps in CBM development as follows: lease play, exploration, field organization, production, enhancement, abandonment, and reclamation.

- Information Sheet #4, Impacts of coal bed methane development on human health, safety, and welfare. Unlike many industrial activities that are located in industrial zones, CBM development often occurs in rural areas where residents are not accustomed to rapid occurrence of impacts such as: water well contamination, human litter, exposure to toxic materials, dust, potential fires and explosions, flooding, traffic congestion, reckless driving, noise pollution, concern about property values, water well depletion or loss, loss of vegetation, and soil contamination. In addition to these specific impacts, stress often increases for people living near CBM developments. This development also impacts public infrastructure. Roads and bridges have increased use and many citizens have questioned whether volunteer fire department can handle the increased risk of fire and hazard material spills that could be associated with CBM development.
- Information Sheet #5, Impacts of coal bed methane development on livestock and wildlife. Under Colorado's rules and regulations, oil and gas producers must compensate landowners for unreasonable crop loss or land damage. However, grass is typically not considered a crop and the monetary value of grass is low compared to its importance in a ranching operation. Bulldozing grass to create well pads and access roads, with the cumulative total disturbed area averaging as high as 5 acres per well, can significantly reduce the amount of grazing land available. A quote from a Wyoming rancher sums up the concern: "We have survived blizzards, drought, depression, uranium activity, and oil activity. None of these compare to the impact we are facing with the discharge of this coalbed methane water on my land. Between the potential loss of hay and the potential loss of accessibility to grazing land, I am out of business." Sometimes produced water is simply discharged on the ground and allowed to run off. When many wells feed the same drainage, flooding of the channel can result. Cattle often seek these drainages for shelter, and especially during calving flooding can pose a risk to young animals. Other concerns relate to livestock fences and impacts on wildlife.
- Information Sheet #6, Impacts of coal bed methane development on the environment. This note refers to the following possible environmental impacts of CBM development: reduced flow or loss of domestic water wells; methane seeps, fires, and explosions; underground coal fires; vegetation die-off; methane contamination of homes and buildings; dust; noise; soil erosion; soil compaction; loss of topsoil; and introduction of weeds. It is noted that most laws to protect public health, safety, and the environment are written from the perspective of individual problems or individual projects with little or no attention to cumulative impacts from CBM development. There is public concern that CBM development is not being viewed in a visionary way.
- Information Sheet #7, Impacts on water wells. One of the most disturbing potential impacts of CBM development is the influence on domestic water wells. There are reports of water wells going dry on the very day that a CBM well had been drilled within 200 m of a water well, but it is difficult to prove that there is a link between the water well and the CBM well. One of the frequent arguments used to refute CBM development impacts on water wells is based on geological stratigraphy. CBM is generally extracted from depths far below most water wells and it is asserted that there is no connection between the water-bearing strata and the coal seams.

However, citizens have argued that their area in southeastern Colorado is fraught with fractures due to the Spanish Peaks uplift, suggesting there can be connections between various geological strata and they contend that there are U.S. Geological Survey and Colorado Geological Survey reports to support this contention.

- Information Sheet #9, Noise. Arrival of CBM development has impacted the quiet of rural areas in Colorado. This is especially so because many citizens live in rural parts of the Raton Basin because of the quiet that it affords. The state of Colorado has regulations to govern noise from CBM development in residential, commercial, light industrial, and industrial zones but there are no levels defined for rural areas. CBM development brings noise from increased traffic, drilling activity, well pumps, and compressors. The noise emitted by well equipment is often a low hum that does not violate state decibel output regulations, but the humming is still an annoyance to those living near it, especially at night. Compressors are the noisiest aspect of CBM development. There are ways to minimize the noise generated by CBM development. However, regulatory agencies typically do not require special noise reduction measures and it is up to citizens to request CBM operators to implement sound-reducing technologies.
- Information Sheet #35, Considerations for a surface use agreement regarding water. Surface use agreements can help landowners protect their water supplies and the following guidelines are suggested for inclusion in such agreements: request a baseline test of all domestic water wells and springs; request water testing at regular intervals; establish damage standards as part of the agreement (for example, if a water well drops below a certain level or changes in quality, specify in advance exactly what water level or quality change constitutes damage); require that CBM wells be cased to at least 50 ft below the depth of all domestic water wells within 1 mile radius of any well; determine in the agreement whether any CBM wells are to be converted to water wells; specify how produced water is to be disposed; consider clauses for protection of local water resources (control produced water flows in relation to culvert capacity, avoid damage to local springs, establish surface water monitoring sites especially near aquatic habits, avoid surface disturbances on floodplains of perennial streams, and prevent water migration up well bores after CBM operations cease).
- Information Sheet #36, Considerations for a surface use agreement regarding surface disturbance and reclamation. Surface use agreements can address surface disturbances and required reclamation of disturbances. Possible clauses for use in such an agreement include: schedule and deadlines for recontouring and revegetation of disturbed areas; avoidance of construction on saturated soils or where watershed damage is likely; limitations on removal of vegetation; avoidance of CBM wells on slopes that require cut-and-fill for well pad construction; avoidance of highly erosive soils; and use of erosion control measures on unstable soils, steep slopes, and wetland areas to prevent erosion and sedimentation until vegetation is reestablished. This information sheet also contains detailed guidelines for reclamation and revegetation of disturbed land areas.
- Information Sheet #37, Considerations for a surface use agreement regarding roads, compressors, and pipelines. CBM-related roads, compressors, and pipelines each result in specific types of surface disturbances. Surface use agreements to protect

landowners against such disturbances can include provisions for: road standards to minimize disturbances to soil and vegetation; placement of water bars on road grades and slopes to avoid erosion; provision for road dust suppression and speed limits; provision that roads no longer required for CBM operations be permanently blocked, recontoured, reclaimed, and revegetated. Similar provisions are suggested for limiting surface disturbances from compressor stations and pipelines.

- Information Sheet #38 Considerations for a surface use agreement regarding wildlife, wildfire, weeds, and other topics. Surface use agreements can cover a broad range of topics and may contain clauses pertaining to: fencing criteria to protect wildlife and wildlife habitat; limitations on use of firearms and pets by CBM personnel; responsibility for fire suppression costs; policies for gates, locks, and security devices; controlled use of insecticides, herbicides, fungicides, and rodenticides; arrangements for weed control at CBM facilities; handling of CBM project debris; burial of electrical power lines to protect people and wildlife; avoidance of wetlands if aboveground power lines are used; design of facilities to minimize undesirable visual impact; and protection of cultural resources.

Edgar, T.V.; Case, J.C. 2000. Pumping induced settlement of aquifers. Wyoming State Geol. Surv., Preliminary Hazards Rep. PHR 00-1. 9 p.

CBM operations are not specifically mentioned in this hazards report but both authors have previously written about subsidence in relation to Powder River Basin CBM development. They indicate that where subsidence has occurred it is typically in unconsolidated clastic sediments laid down in alluvial, lacustrine, or shallow marine environments. If unconsolidated saturated silt and clays are present above and are interbedded with a confined sand and gravel aquifer, pumping from the aquifer can lead to a pore-pressure reduction in the silts and clays and change the stress in the aquifer through artesian head decline. This causes settlement in the aquifer and settlement in the overlying and interbedded silts and clays, which often leads to surface subsidence.

The authors' research showed that the compressibility of water is not a significant factor in aquifer deformation or supply. As the depth of the aquifer increases, the modulus of elasticity increases while the reciprocal bulk modulus decreases slightly. These changes indicate that the compressibility of the aquifer decreases with increasing depth. This is why most regional settlement problems occur in situations with shallow aquifers or sedimentary deposits close to the ground surface.

Ellard, J.S.; Moffett, T.B.; Litzinger, L.A. 1997. Production-related causes of scaling in wells in the Cedar Cove and Oak Grove Coalbed Methane Fields of central Alabama. *In* Proc. 1997 Int. Coalbed Methane Symp., May 12-17, 1997, Tuscaloosa, AL. Univ. Alabama, Tuscaloosa, AL. pp. 235-247.

This article demonstrates that there can be long-term changes in the chemical composition of produced water as production and dewatering of coalbeds proceeds. For example, mixing produced water from shallow coal strata with waters from deep coal strata saturated with calcium carbonate may reduce the pH of the introduced water and cause over-saturation which in turn results in precipitation of scale. The chemistry of waters produced from multiple zone completion wells will change as dewatering of shallower coals increases the contributions of waters from deeper coals. These changes in water chemistry can persist for more than five years and the changes can continue until dewatering reaches equilibrium. Pumping for several years may be necessary before the chemical characteristics of produced water become stable. In this Alabama study, about three years were required for stable chemical condition in the water produced from a single-zone completion well, whereas water produced from a multiple-zone completion well was continuing to change after seven years of pumping. The geological setting and hydrologic interpretations of the chemical makeup of produced water may be used to identify the dominant aquifer within multiple-zone completion wells.

Environmental News Network. 2001. Coalbed methane boom in Wyoming's Powder River Basin. ENN, Thursday, Oct. 18, 2001.

Currently in Wyoming there are more than 5500 producing CBM wells under an environmental impact statement (EIS) completed in 1999 and a supplemental drainage environmental assessment completed in 2001. At the time of the original EIS no one anticipated the rapid development of this resource. Consequently, there is a need for a new EIS now scheduled for completion in May 2002, with a Record of Decision expected in July 2002. The EIS will analyze the effects of drilling 50,000 CBM wells and 3,000 conventional oil and gas wells to be drilled over the next decade. Four Wyoming conservation groups (Biodiversity Associates, Oil and Gas Accountability Project, Powder River Basin Resource Council, and Wyoming Outdoor Council) are promoting concepts of phased development, landowner protection, better monitoring, and alternative technologies.

- Under the concept of phased development, CBM extraction would occur in an organized manner across the basin to concentrate impacts by clustering roads, pipelines, powerlines, compressor stations, and other infrastructure. The suggestions are that one coal seam be targeted at a time to properly gauge underground water impacts and that, before moving onto a new location, full reclamation be completed at previously disturbed sites.
- The key principle of reclamation is to return all resources, both above- and belowground, to the condition they were in prior to development. This includes full reclamation of soils and vegetation, eradication of weeds, restoration of riparian areas, and removal of unwanted roads and reservoirs.
- Potential beneficial uses of CBM produced water include dust abatement, stock watering, creation of wildlife watering areas, enhancement of fisheries, and improvement of riparian zones.

Flores, R.M. 2001. Impacts and issues of CBM development. *In* R.M. Flores, G.D. Stricker, J.F. Meyer, T.E. Doll, P.H. Norton, Jr., R.J. Livingston, and M.C. Jennings. A Field Conference on Impacts of Coalbed Methane Development in the Powder River Basin, Wyoming. USDI, USGS, Central Region Energy Resources Team. Open File Report 01-126. 1 vol.

This two-page website overview concisely lists the main environmental issues associated with CBM development in the Powder River Basin. Without providing details, the article lists the following aspects of CBM development in Wyoming.

- A major impact related to dewatering of coalbeds is groundwater drawdown resulting from lowering the water table. A computer simulation of drawdown attributed to CBM development in the Wyodak-Anderson coal zone during the 15 year period to 2015 indicated maximum groundwater drawdown as much as 550 feet in one part of the study area.
- Another major concern is the effect of surface disposal of produced water and the effect of this additional water on watersheds.
- In produced water from the Powder River Basin, total dissolved solids, pH, chloride, and sulfate concentrations are near or lower than levels recommended for drinking water standards.
- It is expected that surface disposal of produced water may result in erosion or drowning of drainage draws and associated vegetation in the project area.
- Several companies have experimented with re-injecting produced water into sandstones and coalbeds in the Wasatch and Fort Union Formations. Pennaco Energy is presently re-injecting water into an aquifer used by the city of Gillette, Wyoming.
- Groundwater withdrawal from aquifers is a particularly sensitive issue with landowners who use groundwater for livestock and irrigation. Generally, operators have cooperated with landowners by diverting produced water from CBM wells into stock tanks or other holding areas for livestock.
- Another important issue is the effect of water composition on soils. Sodium adsorption ratio (SAR) is a measure of the tendency of sodium to replace other cations in soil, potentially reducing soil permeability. Higher SAR values in produced water may limit surface disposal in some areas depending on where the water is being discharged and soil characteristics.
- The major impact of CBM development on existing coal mining is groundwater withdrawal from the coal beds. Although this does not affect the amount of coal that can be produced, it does reduce the available water for mining operations. In addition, there can be conflicts between owners of coalmines and CBM operators in regard to lost gas due to mining. That is, because water is withdrawn during surface mining, reservoir pressures can be reduced resulting in the liberation of methane stored in the coal, making it unavailable to CBM operators.

Gabello, D.P.; Hayoz, F.P.; McCleary, J.G. 1983. Dewatering systems and techniques. Quart. Review Methane From Coal Seams Tech. 1(2):12-16.

Most coalbeds are also aquifers that must be dewatered to produce methane. This article assesses technical and economic aspects of 1980s oil and gas pumping systems that may be used for coalbed dewatering. The systems evaluated were sucker rod (beam pumping unit), electric submersible, hydraulic jet and piston, gas lift, and gas-assisted plunger lift. A comparison of systems and relative costs for commercial applications showed that as dewatering proceeds change over to a pump with a lower flow rate substantially reduces costs. Conventional oil and gas industry pumps were judged to be suitable for dewatering CBM wells.

Geological Survey of Alabama. 2001. Coalbed methane in Alabama: an overview. Geol. Surv. Alabama, Tuscaloosa, AL. 7 p.

Alabama's CBM industry has expanded greatly in the past decade and 17 fields are now established. Cumulative production exceeds a 1 TCF as of 2001, and combined resources may exceed 22 TCF. The Warrior Coalfield, also known as the Black Warrior Basin, is the largest in the state. Other Alabama CBM resources are in the Plateau Coal Region north of the Black Warrior Basin, and in the Cahaba and Coosa Coalfields of the Appalachians. A low-rank lignite belt in southern Alabama is of questionable value as a CBM resource.

This overview contains a synopsis of the basic facilities required to produce coalbed gas and dispose of formation water. Some major transmission pipelines existed when commercial CBM production began in 1980. Having pipelines already in place was of great value to early producers and now an intricate network of collection and transmission pipelines has been built. The facilities required to dispose of produced water are as complex as those needed to deliver gas to market. In the early 1980s the state permitted land application of produced water with TDS content less than 2000 mg/L, but this practice became infeasible when water with higher TDS was encountered. At present stream discharge is the most common method of water disposal. The type of permit currently offered is termed a Tier II Permit that requires monitoring water quality in streams and limits instream TDS concentrations to 230 mg/L. Most operators maintain a system of treatment and storage ponds for produced water. Synthetic membrane liners are used to prevent leakage of impounded water. In treatment ponds, pollutants are removed by settling and by aeration. Underground injection of produced water is recently of increasing interest to CBM operators because environmental restrictions on instream disposal limit the amounts of water that can be handled. A critical aspect of underground injection is finding a permeable formation with TDS content higher than 10,000 mg/L.

Golden, I.W.; Hall, W.L. 1991. Real time instream conductivity monitoring on the Black Warrior River. *In* 1991 Coalbed Methane Symp., May 13-16, 1991, Tuscaloosa, AL. Univ. Alabama, Coll. Cont. Studies & Coll. Engineering. Tuscaloosa, AL. pp. 25-30.

Real-time instream conductivity monitoring on the Black Warrior River was achieved in innovative ways that meet requirements of regulatory agencies, CBM operators, river users, and site-location owners. Probe deployment systems were required to safely house probes in a river with heavy barge traffic and high sediment loadings. Conductivity data were converted to estimates of chloride levels to provide water quality threshold warnings. The sampling method described by the authors has implications for other industries as well. A monitoring system of this type can be adapted to include other water quality parameters such as dissolved oxygen, oxidation-reduction potential, temperature, salinity, and river stage. Whether owned and operated by the CBM industry or a regulatory agency, a real-time monitoring system can be a useful tool to protect and improve surface water quality.

Gorody, A.W. 2001. Coalbed methane production faces numerous concerns. Oil & Gas J. 99(30):66-67, 70.

The most common complaints attributed to CBM practices in the San Juan, Black Warrior, and Powder River basins are: loss of domestic water quantity; deterioration of either surface or groundwater quality; and accumulation of potentially dangerous concentrations of free and dissolved methane in both water and soils. Because changes in water quantity, water quality, dissolved gas concentrations in water wells, and rates of methane seeps at the surface can all be naturally occurring phenomena, it is important for CBM operators to be supported by data gathered prior to and during the onset of CBM production.

The author cautions against simplistic views to explain declining water yields in domestic wells that might be completed in aquifers hundreds of feet above or below a producing coal horizon. One frequent misconception is that local aquifers have a regional extent and that they are both vertically and laterally homogeneous. The author believes a more reasonable assumption is that many permeable conduits can connect coal seams with underlying or overlying aquifers.

If one assumes that migrating coalbed methane can bubble through a domestic water well, the methane will displace free oxygen and create conditions suitable for a chemically reducing environment. Therefore, increased methane concentration can accelerate the activity of bacteria in the water, with two effects. The first effect increases bacterial waste in the water causing slime and cloudy water. The second effect lowers free and chemically bound oxygen levels that bacteria consume for respiration. This promotes the growth of iron-reducing bacteria (IRB) and sulfate-reducing bacteria (SRB). SRB will strip sulfate ions of their oxygen during respiration. The byproduct of this metabolic process is carbon dioxide and hydrogen sulfide gas. Water containing hydrogen sulfide can corrode plumbing fixtures. IRB will allow iron to readily dissolve in water. Dissolved iron and sulfide ions can combine to form suspended particles of iron sulfide that will impart a dark gray color to the water that stains porcelain fixtures, faucets, and laundry. Bacteria can also be agents of chemical change in increasingly oxidized waters. If oxidation occurs in a well bore containing dissolved iron, then IRB will convert the iron to an iron hydroxide precipitate. This imparts a rusty red color to water. Surface discharge of CBM water can also affect surface water chemistry by changing salinity or modifying background concentrations of metal ions.

Both litigators and regulatory agencies have identified four migration mechanisms to account for methane in domestically used aquifers: vertical migration through large natural fractures; methane migration along access paths provided by well bores and, in some documented cases, domestic water wells; liberation of methane during CBM production as methane migrates updip until it exits from outcrops near basin margins where gas seeps typically emerge along the outcrop belts of producing coal seams; and, alternatively, down-basin production can lower water levels near the outcrop and allow methane to be released at the surface via *in situ* desorption of gas-saturated coal seams.

The author emphasizes the importance of CBM operators to understand the natural dynamics of regional coalbed aquifers and both overlying and underlying aquifers within 100 feet of a CBM producing horizon. Under certain conditions significant local crossflows between aquifers can occur both within and outside the immediate well bore environment.

Ground Water Protection Council. 1998. Survey results on inventory and extent of hydraulic fracturing in coalbed methane wells in the producing states. Ground Water Protection Council, Oklahoma City, OK. 1 vol. (unnumbered).

The U.S. Court of Appeals determined that the definition of underground injection under the Safe Drinking Water Act was broad enough to include hydraulic fracturing of CBM wells. The court remanded the matter back to the Environment Protection Agency for re-examination of the practice of hydraulic fracturing in CBM operations. The Ground Water Protection Council (GWPC) filed a brief supporting the EPA's argument that hydraulic fracturing did not meet the definition of underground injection. The request for rehearing was denied and EPA set out to gather information to assist a regulatory determination on hydraulic fracturing in CBM operations. GWPC carried out a survey in 1997 to determine the extent to which hydraulic fracturing was occurring in CBM operations in each state. This survey also requested information on state-substantiated groundwater contamination that could be directly related to coalbed fracturing. Based on the survey, GWPC believes that additional federal regulations regarding CBM wells are unnecessary to protect underground sources of drinking water. The survey yielded no evidence to support claims by some that public health is at risk as a result of hydraulic fracturing during CBM production. GWPC believes that if additional federal regulations were to be imposed they would not be based on scientific evidence of associated contamination and there would be little increase in protection of public health and the environment. The survey results can be find on website http://www.gwpc.site.net.

Gunter, B. 2001. Alberta field pilot to test CO_2 enhanced coalbed methane recovery. Alberta Research Council, Edmonton, AB. 6 p.

The Alberta Research Council is testing a novel process of injecting CO_2 into Alberta's deep unmineable coal beds to release trapped methane. The process is called Enhanced Gas Recovery and is similar to the practice of using CO_2 injection to enhance oil production. In this process, the waste CO_2 produced from coal-burning or methane-burning power plants is injected in CBM reservoirs to produce more methane, and the cycle continues. An abundance of deep coal beds in North America makes geological storage of CO_2 applicable to many areas where coal-burning power plants are located. However, further testing and demonstration are needed to apply this process to low permeability reservoirs such as found in Alberta and elsewhere.

Hand, M.K.; Smith, K.R. 2001. The deluge: potential solutions to emerging conflicts regarding on-lease and off-lease surface damage caused by coal bed methane production. Wyoming Law Review 1(2):661-693.

CBM production in Wyoming is creating new legal concerns especially questions related to damage from release of water onto land surfaces. The authors, senior staff of the Wyoming Law Review, identify uncertain questions of liability because the vehicle of damage to sites outside the leased premises is water as opposed to other forms of trespass. Wyoming courts have not held that discharge of water upon a neighbouring property is a valid cause of action such as trespass or nuisance. The likely reason is that Wyoming is an arid state and the need to prevent water waste in order to irrigate land efficiently has been the overriding principle of Wyoming's water law. Wyoming's courts have not recognized a coherent cause of action based on the existence of unwanted water.

The traditional principles of oil and gas law suggest that CBM producers will be insulated with respect to damage that CBM water causes to the on-lease surface land. However, off-lease surface damage is a different matter. Large volumes of CBM produced water are causing damage to off-lease lands. Water is a unique vehicle of damage because it has its own body of water law and unique causes of legal action that are distinct from principles of oil and gas law. The authors conclude that Wyoming courts should ignore water law, primarily because CBM water is artificially placed on the surface and intentionally discharged to off-lease lands. They recommend instead that there should be an extension of traditional tort causes of action, such as trespass, nuisance, and strict liability, to situations where off-lease lands have been damaged by CBM water. The authors recognize that operators would assert that water law nullifies any cause of action that off-lease landowners seek to bring, giving the CBM operator immunity. One of the problems is that Wyoming courts define the type of water at issue as either watercourse water or surface water. CBM water does not fit this distinction because watercourse water flows within a well-defined channel and surface water is natural water originating from rain or snow. The authors expect that CBM operators will argue that water law should govern CBM water issues and that the courts should define CBM water as surface water.

The authors describe the option of passing a surface damage act in line with other jurisdictions, obligating prospective CBM developers to pay for any damage caused to the on-lease surface estate as well as to any off-lease landowners affected by released CBM water. Currently, Wyoming off-lease surface owners are frustrated by the lack of a cohesive standard to determine whether and how operators will be liable for damage caused by CBM water. The authors suggest that, guided by fairness and sound economic principles, Wyoming courts and law makers should act to prevent operators from reaping the benefits of CBM production on the backs of surface owners. Some jurisdictions have adopted an extension of the reasonable use doctrine, called the accommodation doctrine. This doctrine is a multidimensional approach that attempts to balance the rights and duties of both mineral operators and surface landowners. The accommodation doctrine does not curtail mineral development; it simply obligates operators to respect the existing surface use and, if possible, to maintain it. In Wyoming it is relevant that these concerns extend beyond agricultural land uses because the growth of residential development means that agricultural producers are no longer the only surface owners affected by CBM development.

Harris, S.C.; Mettee, M.F.; O'Neil, P.E. 1987. Coalbed methane development in Alabama: biological and hydrological conditions of streams draining the Cedar Cove degasification field. Geological Survey of Alabama, Tuscaloosa, AL. 113 p. Purchase from Gas Research Institute, Chicago, IL. GRI-87/0038: $65.00.

A website summary indicated the following content and conclusions of this report:

- Although regulations permit land and stream disposal of CBM produced water, effects of high chloride and iron concentrations in receiving streams is an environmental concern.
- Results of stream samples indicate that the chemical regime of small streams is distinctly changed due to discharge of produced water, but larger streams greatly modify the effects of produced water.
- In streams where active discharge of produced water occurred, surface runoff from coal mines had already significantly affected the integrity of biological communities. Adding CBM produced water to such streams created no significant additional degradation to the already stressed biological systems.
- The Alabama Methane Production Co. water management plan and water quality analysis data are included in the report which can be purchased from the Gas Research Institute.

Harrison, S.M.; Molson, J.W.; Abercrombie, H.J.; Barker, J.F.; Rudolph, D.; Aravena, R. 2000. Hydrogeology of a coal-seam gas exploration area, southeastern British Columbia, Canada: Part 1. Groundwater flow systems. Hydrogeol. J. 8(6):608-622.

CBM production requires groundwater removal to depressurize the coal beds and facilitate methane flow to production wells. Groundwater removal will have hydrodynamic effects on the flow system and an understanding of the groundwater flow system is needed to evaluate these effects. This paper describes the groundwater flow system in the Mist Mountain Formation in the Elk River valley by means of a groundwater flow model and interpretation of hydrochemical and isotopic analyses of groundwater and surface water. The research defined two distinct groundwater groups (A and B). An active, shallow, local flow component (Group A) is recharged in beds that crop out along subdued ridges; this component discharges as seeps along lower and mid-slope positions in the southern part of the study area. The authors concluded that groundwater contributes less than 10% of the total direct flow to the Elk River, as indicated by flow measurements and by the absence of Group A and Group B characteristics in the river water. Thus it is hypothesized that groundwater extraction during CBM production will have little impact on the river.

Harrison, S.M.; Molson, J.W.; Abercrombie, H.J.; Barker, J.F. 2000. Hydrogeology of a coal-seam gas exploration area, southeastern British Columbia, Canada: Part 2. Modeling potential hydrogeological impacts associated with depressurizing. Hydrogeol. J. 8(6):623-635

A three-dimensional, finite element flow model was used to assess the hydrogeological effects of depressurizing coalbeds lying in the Weary Creek exploration block, Elk River valley, southeastern British Columbia. The simulation results permit, at an early stage, assessment of the environmental and economic implications of how the flow system may respond to depressurization. The simulations suggest that depressurizing has little effect on groundwater flux to the Elk River. Simulated water production for three depressurization wells operating under steady-state, single-phase flow for reservoir conditions of 13 and 16.5 cm^3/g is 645 m^3/d (4,057 barrels/d) and 355 m^3/d (2,233 barrels/d), respectively.

Groundwaters collected from monitoring wells have relatively low salinity, ranging from about 250-1,300 mg/L. The groundwater is supersaturated with respect to Ca-Mg-Fe-carbonates (calcite, dolomite, and siderite) and Al-bearing silicates, including kaolinite and illite. Dissolved trace-metal concentrations are low; only Fe, d, Cr, and Zn exceed Canadian water quality guidelines for aquatic life. Groundwaters were devoid of the more soluble monocyclic aromatic organic compounds, including benzene, toluene, ethylbenzene, and polycyclic aromatic compounds, including naphthalene.

Harte, J. 2001. Methane boom could be bust for wildlife. Univ. Wyoming, Communications Dept., Laramie, WY. 3 p.

The Bureau of Land Management's environmental assessment of a CBM development area in the Powder River Basin addressed likely effects on wildlife and habitat. A key point was that no detrimental impacts were expected for black-footed ferret (an endangered species) and bald eagle (a threatened but not endangered species). BLM specified seven special status species that require site-specific protective measures (bald eagle, black-footed ferret, black-tailed prairie dog, swift fox, mountain plover, sturgeon chub, and Ute-ladies' tresses orchid). Site-specific measures can include restrictions on CBM drilling at certain times of the year, totally banning drill sites in some locations, or establishing noise limits. BLM mandates the site-specific measures.

The assessment defined four criteria for good habitat: existence of plant diversity; presence of structural diversity in the vegetation; presence of habitat edges; and interspersion of different habitat types at the landscape scale. A positive effect of CBM development is an increase in area of surface water made available for wildlife and fisheries development, with some CBM companies promoting fish habitat development by creation of reservoirs from CBM produced water. Negative effects on wildlife are mainly a result of increases in human presence. One additional noted effect of CBM development is reduction in sage grouse populations because new power lines to supply CBM operations provide additional perches for raptors (golden eagle and other hawks) that are reducing sage grouse populations. Regional biologists emphasize that it is difficult to gauge the overall cumulative impact of habitat fragmentation that results from CBM development.

Hinchman, R.R.; Negri, C. 1997. Treating produced water by imitating natural ecosystems. Argonne Nat. Lab., Energy Systems Div., U.S. Dept. Energy, Argonne, IL. 2 p.

The water treatment approach described here refers to saline water from natural gas wells but is also potentially applicable to CBM produced water. Argonne National laboratory has developed a low-cost method for cleaning up and reducing the volume of produced water. Based on phytoremediation, the method uses green plants in an engineered ecosystem modeled on natural wetlands. When selected, adapted plants are grown in contaminated wastewater by hydroponic techniques, the root systems function as a biological filter. An advantage of phytoremediation over physico-chemical technologies, such as ion exchange, is the ability of selected plant species to absorb contaminant ions from an extremely broad range of concentrations. Another advantage is that certain plants have the ability to adsorb target contaminants while ignoring other ions in solution. Over 80 plant species have been screened for salt tolerance and high evapotranspiration rates. In these selected species, evapotranspiration rates are consistently above open-water evaporation rates at saline concentrations of at least 2% salt in the solution.

Horn, C.R. 1990. Environmental management of coalbed methane. *In* C.R. Horn. Chap. 10. Produced waters from coalbed methane wells – state and federal regulations. Alabama Dept. Environ. Manage., Montgomery, AL. 1 vol. (various paging).
Studies of CBM operations in Alabama revealed that wastewater occurred from three different sources: the drilling/fracturing process; non-point runoff from constructed but un-stabilized roads, pads, and stream crossings; and from water produced during the dewatering of the coal seam. Plastic lined pits were generally constructed for retention of drilling and fracturing fluids, with land application of pit contents when development was completed. Sometimes these pits overflowed onto adjacent land. Of the three sources of wastewater, the potential for most widespread environmental impact is from produced water. The redeeming characteristic of produced water in the Alabama study area is its relatively low volume, which with the relatively high tolerance of freshwater ecosystems to chlorides and dissolved solids, allows some management opportunities where produced water is placed in larger streams. For smaller streams, the multiple effects of several discharges are significant. The report lists the following potential pollution sources from CBM production including: produced water; overflow or spillage of fluids used in well development; spillage of chemicals stored on-site during drilling; construction runoff from site grading, road construction, and pipeline installation; holding pond overflow or leakage; pipeline leakage; and runoff from land application. One result of the author's review was a 'best management practices' plan for coalbed methane. That plan addressed topics such as: general erosion control techniques; road construction; drilling pad and pit construction; pipeline construction; stream crossing guidelines; erosion control plans; general water use; use of water for dust suppression; maintenance and inspection criteria; operator responsibility; emergency response measures; and well closure guidelines. Too detailed to annotate, Attachment 3 of this report contains specific guidelines for the above-listed components of a CBM best management practices plan.

Horpestad, A. 2001. Water quality analysis of the effects of CBM produced water on soils, crop yields and aquatic life. Montana Dept. Environ. Quality, Billings, MT. 8 p.
CBM discharge water contains several substances that could, at certain concentrations, be harmful to aquatic life or use for agriculture. These substances include: sodium, bicarbonate, sodium amount relative to calcium and magnesium (SAR), and total dissolved solids (TDS). Determining TDS of water samples requires chemical analysis in a laboratory which is time consuming and costly. Because ions dissolved in water conduct electricity, electrical conductivity of water (EC) is a relatively good measure of TDS. Determining EC is inexpensive and can be done at the site, and it can also be continuously recorded. EC of irrigation water is important because after a given threshold of EC in the soil water, further increases cause declines in crop yield. In the Powder

River drainage, the EC of CBM water may be nearly the same as EC of the surface water. Because of their similarity, CBM discharges will likely have little effect on the median values but may increase the EC during periods when irrigation occurs. Thus maximum increases in EC may need to be limited during the period when irrigation is taking place. When natural EC levels exceed the threshold levels, discharge of CBM water could still occur without affecting crop yields provided such discharge does not cause increases of instream concentrations.

Horpestad, A. 2001. Water quality criteria for irrigation in CBM areas. Montana Dept. Environ. Quality, Billings, MT. 11 p.
In Montana, numeric water quality standards have not been adopted for salinity, generally expressed as electrical conductivity (EC) nor for sodium adsorption ratio (SAR). The Montana Department of Environmental Quality is attempting to determine levels of EC and SAR that will not affect use of CBM water for irrigation. The department will post information on development of these standards on its web site at http://www.deq.state.mt.us/coldbedmethane/events.asp. The effects of EC and SAR of irrigation water on soils and crop production are dependent on interactions of several factors other than water. These factors and their interactions are discussed in this article.

Hupp, K.L.; Bibler, C.; Pilcher, R.C. 1999. Recovery of methane from the abandoned Golden Eagle Mine property. *In* 1991 International Coalbed Methane Symp., May 1991, Tuscaloosa, Al. Univ. Alabama, Tuscaloosa, AL. pp. 449-461.
The abandoned Golden Eagle underground coal mine in Colorado is an example of relations between former coal mining and current CBM production. This former mining area contains gassy coals from which Stroud Oil Properties Inc. (Stroud) has been recovering methane since 1996. The mine closed in 1996 and during its operation drained methane from gob and ventilation boreholes. Stroud currently produces pipeline quality methane from six of these boreholes. Overburden relaxation and modeling indicate that overlying coal seams and the coal remaining at the margins of the mined-out workings contribute a significant amount of gas to current CBM production. Recovery of methane from this abandoned mine has proven challenging. First, the mountainous terrain made access and pipeline construction difficult. Many of the roads originally used to monitor the drainage boreholes required upgrading to allow truck travel and access for pipeline equipment. Second, air contamination from leaking drainage boreholes initially hindered the project because it diluted the methane below pipeline requirements. Stroud solved this air contamination problem by sealing the shafts and boreholes, and by reducing suction to a level that did not pull in excessive amounts of air.

Hurtt, III, W.C. 1997. Produced water evaporation enhancement project for the Drunkards Wash Field, Carbon County, Utah. *In* Proc. 1997 Int. Coalbed Methane Symp., May 12-17, 1997, Tuscaloosa, AL. Univ. Alabama, Tuscaloosa, AL. pp. 453-458.
For years, evaporation has been an accepted industry practice for disposal of produced water. This paper describes the planning, development and implementation of a program to augment water disposal at evaporation ponds.

- In this study, techniques originally considered for increasing evaporation in ponds were spray application, waste heat recovery, and aeration. Evaporation enhancement through spray application was chosen as the most promising method for economic and engineering reasons.
- The basic flaws in any evaporation program are the large surface area required to achieve an acceptable daily evaporation rate, and the extreme salinity of water that remains in the system. Large surface area is a problem due to the economic, environmental, and legal liabilities that exist in conjunction with any large reservoir.
- This study concluded that there are three enhancement alternatives worthy of further inspection. These included aeration by introducing compressed air into the pond through a manifold system below the water surface. While the theory behind aeration is sound, the volume of air required per unit of evaporated water makes the process too costly. The second alternative, waste heat recovery, is attractive for enhancing evaporation as it can harness otherwise wasted energy at compressor stations. The major drawback to using waste heat recovery is the high capital cost of the heat exchangers used in the process. The third alternative, spray application, simply involves introducing produced water to the air through spray nozzles designed to emit the smallest possible droplets. The simplicity of this alternative led to selection of spray application as the most promising method to examine in further pilot tests.

Hydrometrics, Inc. no date. HYDRO water treatment system for treatment of produced water in the Powder River Basin of Wyoming. Hydrometrics, Inc., Helena, MT. 3 p.

Many CBM producers in the Powder River Basin are seeking a cost effective option for treating CBM produced water. Treated water would likely be discharged to receiving streams or applied directly for agricultural use. The treatment system waste stream would likely be placed in surface ponds or in injection wells. Hydrometrics, Inc., has developed a simple and flexible treatment process called HYDRO that cost effectively treats CBM water. It treats only those parameters of concern – sodium, hardness, and certain metals. The process involves the following steps: weak acid cation (WAC) ion exchange; forced draft decarbonization; lime addition; and ion exchange regeneration. The HYDRO process involves passing water through a bank of ion exchange vessels with no high-pressure pumps or complex system of pipes and valves. Therefore, the system can be skid mounted for easy transport between sites. HYDRO's design features are flexible to allow adjustments for meeting different standards or operating conditions. The TDS and SAR variables are controlled independently. If a regulatory agency changes treatment requirements, the system can be adjusted to accommodate changes without a major retrofit. The same is true if produced water characteristics change from one location to another.

Hydrometrics, Inc. 2001. Pilot testing high efficiency reverse osmosis on gas well produced water. Hydrometrics, Inc., Helena, MT. 1 p.

An average CBM well in the San Juan Basin delivers 20-50 barrels of produced water per day. This water is trucked to deep injection wells at a substantial coast. Reverse osmosis systems had been tested before but had not been economical because of the high cost of membrane cleaning and replacement in this area where produced water contains barium, strontium, coal fines, and hydrocarbons that are difficult to filter out.

Hydrometrics, Inc. tested a new reverse osmosis system that pre-treats the water with a special ion exchange resin to remove hardness and divalent metals. The water is then acidified and degasified to remove alkalinity, and pH of the water is increased to 10 before it is fed to a reverse osmosis unit. This patented process is called High Efficiency Reverse Osmosis (HERO®). In conventional reverse osmosis systems, membranes foul with scale, organics, and microbial growth. The HERO process eliminates this problem by removing the divalent metal ions and then operating the reverse osmosis system at a high pH where organics are emulsified and biological growth does not occur. The produced water delivered to the HERO system contained about 14,000 ppm TDS, 7,000 ppm alkalinity, 25 ppm total suspended solids, and 5 ppm hydrocarbons. The silt density index was greater than the test could measure. The system was operated for two months and product water exceeded EPA drinking water standards for all parameters through the test period. No evidence of membrane fouling was observed, and this substantially reduced the disposal cost of produced water. More importantly, the test demonstrated that this method of reverse osmosis could be used to treat extremely fouling wastewater that contained oil and high molecular weight organic matter.

Jeffrey, J.G.; Hinkel, J.J.; Nimerick, K.H.; McLennan, J. 1989. Hydraulic fracturing to enhance production of methane from coal seams. *In* 1989 Univ. Alabama Coalbed Methane Symp., April, 1989. Univ. Alabama, Tuscaloosa, AL. pp. 385-394.

This paper describes laboratory experience and several simple models of processes believed to occur during hydraulic fracturing of coal. The modeling of hydraulic fracture growth is greatly hampered by lack of data. There is evidence that high levels of coal fines occur during hydraulic fracturing. It is assumed that such fines are taken up by the fracturing fluid and results in large changes in the fluid's properties. The slurry becomes even more concentrated due to continuous creation of fines and loss of fracturing fluid during the treatment. Several inexpensive surfactants are effective in enhancing the dewatering of both non-oxidized and highly oxidized coals. The authors recommend that surfactants be used in remedial work-over treatments in wells where dewatering and methane production appear to be severely retarded and in wells where fines present production problems.

Johnson, D.G.S.; Smith, L.A. 1991. Coalbed methane in southeast British Columbia. Min. Energy, Mines & Petroleum. Resources, Victoria, B.C. Spec. Pap. 1991-1. 19 p + maps.

This article does not address water handling or other environmental aspects of CBM development, but it demonstrates a factor that could influence where CBM extraction is most likely to occur. In the case of southeast British Columbia, a favorable factor is that road access is already in place as well as other infrastructure such as a 36-inch gas pipeline tied to United States markets.

Journal of Petroleum Technology. 1996. Alternative dewatering system – coalbed methane wells. J. Petrol. Technol. 48(8):699-700.

The most common systems for dewatering CBM wells involve pumping systems such as sucker rod, electric submersible, progressive cavity, or gas lift. An alternative dewatering system using the hydraulic gas pump (HGP) is described. Its operational advantages include: gas does not interfere with its operation; it resists damage from solids by eliminating the lift mechanism; it has a flexible production rate and is suitable for all production phases of CBM wells; and it is a wireline-retrievable system. The HPG system has fewer problems than other pumps in environments where CO_2 or corrosive fluids are present. It also has economic advantages because it has fewer subsurface failures than most existing pumps. In particular, the HGP mechanism is not subject to damage by sand or coal particles.

Kaiser, W.R.; Swartz, T.E. 1989. Fruitland Formation hydrology and producibility of coalbed methane in the San Juan Basin, New Mexico and Colorado. *In* 1989 Univ. Alabama Coalbed Methane Symp., April, 1989. Univ. Alabama, Tuscaloosa, AL. pp. 87-97.

At the time of this article, little was known about the hydrology of coal basins and the relation of hydrology to producibility of methane. The significance of hydrology was evident in the need to dewater some coal seams to stimulate gas desorption but, beyond this correlation, few associations had been established between the regional hydrologic setting and methane producibility. This study by the Bureau of Economic Geology, University of Texas at Austin, evaluated the role of fluid flow, pressure regime, and hydrochemistry in the producibility of San Juan Basin methane. In that basin the Fruitland Formation is overpressured in the north-central portion and underpressured in the southern part. The overpressuring is attributed to artesian conditions that involve an elevated recharge area and aquifer confinement in the north part of the basin. Overpressuring as a result of such artesian conditions enhances, but is not required for, CBM production. Sustained production can also come from underpressured coals. Fruitland Formation waters are chemically diverse and reflect the hydrologic setting rather than their producing lithology.

Kaiser, W.R.; Scott, A.R. 2001. Application of hydrogeology to coalbed methane exploration and development. *In* 2001 International Coalbed Methane Symp., Tuscaloosa, AL. Univ. Alabama, Coll. Continuing Studies, Tuscaloosa, AL pp. 299-382.

In CBM development, hydrogeology is important for operational reasons and for delineation of reservoir conditions. Hydrology of coal beds is important because the coal must be dewatered (depressured) to initiate gas desorption for commercial CBM production. Some key points from these short-course notes are as follows:

- Data on CBM water production for six western U.S. basins indicate that gas/water ratios vary widely among basins, as does water chemistry.
- Hydrologic studies assist reservoir characterization because hydraulic gradient, pressure regime, and hydrochemistry define an aquifer's ability to accept and transmit fluids. Detailed evaluation of regional hydrology indicates how fluids

migrated in the basin over time and space, thereby allowing predictions of areas of greatest CBM production.

- Hydrogeology is also important because it can indicate the amount of produced water to expect; disposal of produced water carries a cost ($0.15 to $2.00/barrel).
- Hydrogeologists use a variety of tools (ranging from maps to numerical models) and variables such as distribution of potential energy (hydraulic head) and mass (dissolved solids) to identify regional groundwater circulation patterns and to indicate permeability anisotropy. Reservoir conditions can be inferred from hydraulic gradient, pressure regime, and hydrochemistry.
- Hydrogeological conditions are a major control on the occurrence and producibility of coalbed methane, which is greatest from artesian coalbeds that are associated with discharge areas or coalbeds that exhibit upward vertical flow.
- The chemical composition of coalbed waters reflects the hydrologic setting rather the producing lithology.
- In the San Juan Basin, regional overpressuring is artesian in origin. Artesian overpressure can be promoted or limited by fault systems. Hydrocarbon overpressure in the deep portion of basins is predicated on low permeability and active generation of gas. The Raton Basin is underpressured because of limited recharge, low permeability, and the draining effect of igneous dykes and sills. The Raton Basin system is not accepting and retaining enough water to become pressurized.
- The presence and distribution of low-chloride formation water indicate dynamic fluid flow and permeable pathways. Saline waters indicate restricted flow or limited recharge, or both. Chemical composition records actual groundwater movement (mass transfer), whereas hydraulic head shows the direction of force that drives the groundwater flow. Thus, the distribution of these variables identifies regional groundwater circulation patterns and indicates permeability anisotropy.
- Coalbed methane is produced in a variety of hydrologic settings. In the San Juan Basin, production is greatest along a regional permeability barrier, or no-flow boundary, in association with convergent upward flow. Barriers to lateral flow (facies changes and faults) are the most important causes of upward flow, which is dependent on vertical permeability, an important but overlooked flow parameter in CBM production.
- Although overpressure is not required for CBM production, such production is highest from artesian coalbeds. Wells are water productive in response to artesian conditions and wells completed in underpressured coals commonly produce little or no water.
- It may be economically impossible to dewater some coalbeds because of their high permeability and proximity to groundwater recharge areas.

Kennedy, A. 1998. CBM – a viable energy option? GeoDrilling 6(9):2-3.
This note contrasts the success with CBM development in the San Juan and Black Warrior Basins of the United States with the generally unsuccessful attempts at CBM production in Canada, United Kingdom, and in eastern Europe. The lack of success in the latter areas is commonly attributed to unsuitable coal permeability. At the time of this article, additional experimental CBM operations were underway in the United Kingdom, particularly in Nottinghamshire. In anticipation of CBM well spacings as close as 150 m

there was concern that the development might not be environmentally acceptable in the United Kingdom test sites. Increased use of directional drilling was being examined as a way to lessen surface impact of CBM operations in densely populated areas.

Kuuskraa, V.; Kelafant, J.; Kuuskraa, J.A. 1997. A critical look at the geologic and reservoir controls on producing Appalachian Basin coalbed methane. AAPG Bull. 81(9):1556. Abstract.

The central and northern Appalachian Basin is the birthplace of the CBM industry, with gas production from coal seams dating to the early 1920s. However, the basin has only recently emerged as a significant production area. While ownership issues hampered development of the CBM industry during the 1980s, it was lack of adequate reservoir characterization that prevented the basin from reaching its CBM production potential. Coal seams of this basin have distinctly different reservoir properties from the Black Warrior and San Juan basins. Failure to recognize these differences led companies to use inappropriate completion and production technologies. For example, the early use of gelled stimulation fluids in the relatively dry Pocahontas coals seams caused serious formation damage and impaired the performance of CBM wells. This paper reviews completion and production technologies appropriate to the Appalachian Basin.

Lambert, S.W.; Graves, S.L. 1989. Coalbed methane – 5. Production strategy developed. Oil & Gas J. 87(47):55-56.

Two methods are used in the Black Warrior Basin to dispose of CBM produced water: land application and stream or river discharge. Direct land application is used when water contains total dissolved solids concentration of less than 2000 ppm, a criterion established by the Alabama Department of Environmental Management (ADEM). For land application, the water runs through a pipeline from the well to a vegetated area where it is distributed by sprinkler. If the produced water does not meet ADEM requirements, it is treated either by dilution or with aeration in settling ponds. CBM water is discharged into streams or rivers if the downstream quality of the stream or river does not decrease below the standards specified in discharge permits granted by ADEM.

Lang, K. 2000. Coalbed methane trends. PTTC Network News 6(2nd. Quarter):1-8.

Over the past ten years CBM has gone from being a coal mine nuisance to a high-cost scientific curiosity, to a ‘one-play-wonder’, to a low-cost, low-risk source of long-term reserves. The author, representing Hart Energy Publications and Hart/IRI Fuels Information Services, noted that a common feature of CBM plays is that each one is different. In some cases, the water produced is fresh enough for beneficial uses. In the Powder River Basin ranchers are stocking CBM water disposal ponds with fish. Unexpectedly, one environmental issue has developed not from water being produced from CBM wells but from the compounds pumped into the wells. For example, an Alabama court case in 1989 led to a situation where CBM wells are now subject to underground water injection regulations because of fracturing fluids used. This means that fracturing fluids must now be certified as meeting primary drinking water standards. Throughout the legal process in Alabama no evidence was found for any actual groundwater contamination from CBM well fracturing procedures. Although none of the substances added to fracture stimulation fluids is considered a contaminant by the EPA, the water itself must meet the standard, and most streams and lakes in Alabama are not potable. The result is that CBM operators must buy and transport water from public water systems to formulate a fracturing fluid that is more drinkable than natural surface water at the well location. This website newsletter (http://www.pttc.org/tech/news/v6n2nn7.htm) reproduces a table from the literature that describes each of seven major United States CBM basins in terms of: number of producing wells (1996); cumulative CBM production (1981-1996); typical net coal thickness; typical gas content; typical well spacing; average gas production per well; and estimated finding cost per Mcf of gas.

Lawrence, A.W. 1993. Coalbed methane produced-water treatment and disposal options. Quart. Rev. Methane From Coal Seams Tech. 11(2):6-17

This article describes: use of an engineering-economic model to identify cost effective water treatment technologies; and case studies of produced water management in the Black Warrior and San Juan basins. This research was done by Remediation Technologies Inc. under contract to the Gas Research Institute (GRI) and is itemized below:

- In the San Juan Basin the practice in 1993 was to dispose of CBM water in saltwater disposal wells. GRI found that projected water volumes from CBM activities would exceed the capacity of existing disposal wells. Surface discharge would not be feasible without pre-treatment to reduce salinity and total dissolved solids (TDS).
- CBM water production rates generally decline with time, whereas water rates in conventional gas wells may increase as gas is depleted. The estimated 1991 produced water volumes in the United States show the relative amounts produced by CBM *versus* non-associated gas operations:

	Percent total gas produced, 1991	Percent total water produced, 1991	Produced water volume (MMbbl/yr), 1991
Onshore non-associated gas	68.0	62.7	285
Offshore non-associated gas	29.2	23.7	108
Coalbed methane	1.3	13.4	61
Total produced water for all oil and gas operations	-	-	14,000

- As the figures above indicate, CBM operations contributed less than 2% of total U.S. gas production in 1990, but they accounted for about 13% of the produced water volume. When compared to total produced water for the entire oil and gas industry (14,000 MMbbl/yr), the contribution of CBM water was still relatively minor in 1990. On a unitized basis, CBM water averages 0.31barrels water/MCF gas, whereas conventional non-associated gas yields 0.023 barrels water/MCF gas. A unit volume of CBM on average produces 13.5 times the amount of water as a unit volume of conventional non-associated gas. Thus, economic management of produced water is a critical issue for CBM development.

- The authors emphasized that specific chemical concentration information is essential for optimal management of a particular source of produced water. The fact that CBM waters have much lower (if any) concentrations of dissolved organic compounds, such as benzene and toluene, simplifies the treatment systems required to satisfy surface discharge permit criteria.
- The single most critical parameter to characterize water quality is TDS because it is usually associated with undesirable impacts on aquatic organisms and drinking water sources, and may also influence injection formation fluid chemistry compatibility.
- Viable treatment and disposal options for produced water must focus on total or partial demineralization and possibly aerobic biological treatment for destruction of trace organics. Alternatives to reinjection will be more easily obtained with CBM produced waters because of their lower concentration of TDS and dissolved organics compared to produced water from conventional non-associated gas.
- The end result of this research was a PC-based Produced Water Management Options Model, with which a user can evaluate produced water treatment and disposal options in relation to various management scenarios ranging from discharge to surface waters to disposal in Class II injection wells.
- Five potential discharge options are incorporated into the model based on an understanding of the existing regulatory framework: deep well injection with no pre-treatment; deep well injection with pre-treatment; surface water discharge under NPDES permit; treatment of water for beneficial use under NPDES permit; and zero discharge, assuming evaporation to dryness and disposal of residual solids in a permitted landfill.
- A summary of Black Warrior Basin experience indicates that: operators can achieve permitted discharge levels of instream chloride concentration outside the mixing zone by a combination of effluent treatment, storage, release, and instream monitoring; state-of-the-art water treatment in the Black Warrior Basin combines aeration and gravity settling; and the GRI manual described in this article may provide useful insights to CBM operators in other regions.
- When this article was written, GRI was beginning additional research on several topics: feasibility studies of partial demineralization of produced water by electrodialysis and combined electrodialysis-reverse osmosis; evaluation of thermomechanical evaporation processes for partial demineralization of produced water; evaluation of a natural freeze-thaw/evaporation process for management of produced water in northern areas such as Colorado and Wyoming; and evaluation of a fluidized-bed biological reactor for removing dissolved organics from produced water.

A very useful part of this report is the list of representative values for chemical quality of produced water from conventional non-associated natural gas fields versus CBM fields (abstracted from the GRI database). Representative concentrations of constituents typically found in CBM produced water are shown in the following table.

Parameter	Concentration (mg/L)		Parameter	Concentration (µg/L)
TDS	4,000		Aluminum	40
Chloride	2,000		Antimony	30
Sulfate	12.9		Barium	2,780
Silicon dioxide	7.3		Cadmium	5
Bicarbonate	597		Calcium	89,000
Fluoride	2.6		Chromium	3
Nitrate	3.0		Copper	5.6
Total hydrocarbon	0.21		Carbonate	7.5
			Iron	10,000
			Lead	55
			Lithium	92
			Magnesium	89,000
			Manganese	250
			Mercury	0.13
			Nickel	29
			Potassium	7,500
			Selenium	25
			Silver	1.1
			Sodium	1,906,000
			Strontium	4,000
			Vanadium	5
			Zinc	109

Lee-Ryan, P.B.; Fillo, J.P.; Tallon, J.T.; Evans, J.M. 1991. Evaluation of management options for coalbed methane produced water. *In* 1991 Coalbed Methane Symp., May 13-17, 1991, Tuscaloosa, AL. Univ. Alabama, Coll. Cont. Studies, Coll. Engineering, Tuscaloosa, AL. pp. pp. 31-41.

The Gas Research Institute examined feasibility and costs for treatment and disposal of CBM produced water. Analyses of waters from the Black Warrior Basin and from an aquifer in Wyoming were used in the study. The comparative evaluation of disposal economics addressed three alternative technologies – reverse osmosis, electrodialysis, and evaporation. An additional management technology, deep well injection, was also evaluated. Key findings were as follows.

- Produced water composition varies according to several factors including well location, depth of coal seams, and local hydrology.
- Variables in CBM waters that are likely to require treatment include total iron and biochemical oxygen demand. Therefore, treatment of water to reduce total iron is a typical requirement before discharge. Chlorine concentrations are typically monitored instream at the mixing zone, and levels vary depending on effluent flow rate and surface water flow at the point of discharge.
- Aeration followed by sedimentation effectively handles iron and biological oxygen demand. A typical treatment system consists of two 10,000 gal. open-top aeration tanks operated in parallel, which discharge to a lined pit for suspended solids

precipitation and additional aeration. Such a system can reduce iron levels to below 3 mg/L.

- An alternative is a more sophisticated system that includes an aeration basin, air supply equipment, diffusion equipment, and a blower building.
- Reverse osmosis is a pressure-driven process that separates wastewater into a purified permeate and a residual concentrate by selective separation through a semi-permeable membrane. Dissolved solid levels of 100 mg/L or less can be obtained by reverse osmosis.
- Electrodialysis is a membrane separation technology that uses an electric potential gradient separated by a membrane to remove dissolved salts from solution.
- For this study evaporation was defined as the process of bringing a liquid to its boiling point and vaporizing the volatile components. Because evaporation produces a nearly pure vapor, there is essentially 100% removal of dissolved solids.
- Reverse osmosis, electrodialysis, and evaporation can all remove total dissolved solids to varying degrees. Evaporation has the highest removal efficiency, at nearly 100%, but is the most costly of the three alternatives. Reverse osmosis and electrodialysis are relatively close in cost.
- All three of these more advanced treatment technologies were more expensive than the practice typically used for CBM produced water – aeration and sedimentation followed by discharge to the surface.
- Overall, aeration with sedimentation is the lowest cost alternative followed by reverse osmosis, electrodialysis, deep well injection, and evaporation in order of increasing cost.

Lorenzetti, M. 2001. Policymakers eye regulation of fracturing to protect groundwater. Oil & Gas J. 99(37):40.

In autumn 2001, Congress and the White House were examining what role, if any, the government should play in regulating hydraulic fracturing. The question arose in relation to CBM drilling in the Rocky Mountain region where some environmental groups say the practice endangers underground drinking water sources; state oil and gas agencies in areas with CBM production disagree. In comments to the EPA, industry officials maintain that hydraulic fracturing, which involves injection of fluids into underground formations, is not the kind of underground injection the federal drinking water law was meant to regulate. In July 2001, EPA requested comments on the use of hydraulic fracturing in CBM wells. The comment period ended August 29 and regulators are analyzing the responses to see what action, if any, should be taken.

Luckianow, B.J.; Burkett, W.C.; Bertram, C. 1991. Overview of environmental concerns for siting coalbed methane facilities. *In* 1991 Coalbed Methane Symposium Proceedings, May 13-17, 1991, Tuscaloosa, AL. Univ. Alabama, Tuscaloosa, Coll. Cont. Studies, Coll. Engineering, AL pp. 1-11.

Large-scale CBM development such as experienced in Alabama's Black Warrior Basin during 1989 and 1990 strains the capability of CBM operators and regulatory agencies. Because of this, the authors emphasize that environmental awareness must be incorporated into planning at the outset of a project and maintained through the project. The initial areas of environmental concern in the siting of CBM facilities in Alabama were: wetland disturbances and impacts of dredging and filling in streams; non-point source pollution control; and spill prevention control and counter measures. In the authors' experience the impact on wetlands is the single most critical regulatory issue during establishment of CBM-related pipelines, roads, and pads. This paper reviews the criteria for wetland identification focusing on hydric soil conditions, vegetation types, moisture levels, and flooding conditions. For non-point source pollution the paper addresses best management practices for facility siting to minimize erosion potential. Topics include guidelines for locating roads relative to topographic features, stream crossing constraints, locations of treatment ponds, and soil erosion characteristics. Below are some of the report's main guidelines to address best management practices:

- Operation of CBM facilities often requires some activity in wetlands. If wetlands are considered at the onset of planning, most facilities can be located in non-wetland areas. Clearly, site planning to avoid wetlands is the best way to avoid problems.
- The authors urge CBM operators to have a sound policy to handle non-point source pollution especially criteria to avoid sedimentation as a result of soil erosion. Sedimentation reduces stream capacities, interrupts ecosystem processes, carries other pollutants into water bodies, and may cause other environmental problems. Detailed practical guidelines for erosion control techniques to be used during CBM facility construction are given in this article.
- Guidelines, too detailed to annotate, are presented for CBM-related road construction, drilling pad location and construction, and pipeline location and construction.
- The authors emphasize that addressing environmental concerns as they arise reduces the need for additional regulation. In addition, benefits from environmental awareness will be reflected in efficient operation of CBM facilities and help promote continued success of the industry.

Luckianow, B.J.; Hall, W.L. 1991. Economics of production water storage. *In* 1991 Coalbed Methane Symp., May 13-17, 1991, Tuscaloosa, AL. Univ. Alabama, Coll. Cont. Studies, Coll. Engineering, Tuscaloosa, AL. pp. 57-68.

Economic development of CBM requires a produced water management strategy that allows year-round operation of the well field even during periods of low streamflow. In most cases, storage of water is the preferred alternative over field shut-in. This paper reviews selected storage alternatives, design requirements, construction constraints, regulatory requirements, and costs. The authors, representing Taurus Exploration, Inc., and Dames & Moore, respectively, present an overview of design options for handling large volumes of produced water during periods of low streamflow. This is a major economic choice because costs of produced water storage must be balanced against the potential revenue loss and well damage associated with well field shut-in. Key points made by the authors are:

- Use of instream dilution as a disposal technique is critical to the economics of CBM recovery. However, dilution as a management technique requires coordination of produced water flow with the variable assimilation capacity of receiving streams in the well field.
- The capacity of a receiving stream to assimilate produced water discharge is a function of seasonal variation in streamflow, produced water chloride concentrations,

variability in discharge rates, and permit criteria. The most critical periods are typically during project start-up and in the months of low streamflow.

- Four variables must be considered in relation to produced water flow: per well flow rates; well flow rate variation over the life of a project; water quality; and total discharge into the receiving basin.
- In the United States, the National Pollutant Discharge Elimination System (NPDES) defines allowable mixing zones, allowable chloride concentrations at the edge of the mixing zone, and criteria for discharge shut-in. NPDES permits contain the provision that the mixing zone may only encompass 50% of the stream width.
- If produced water cannot be released to streams, water must be stored. The alternatives available for lined storage ponds are plastic liner, bentonite-clay liner, bentonite slurry walls, and hydraulic barrier. Too detailed to annotate, information is provided on the choices between conventional lined storage, slurry walls, and hydraulic barriers. Flexible membrane liners or geomembranes have been used for dependable seepage control in many surface impoundments. The hydraulic barrier approach depends upon maintaining a positive hydraulic gradient into the storage facility. The hydraulic barrier requires the presence of a freshwater barrier with a potentiometric surface higher than the maximum level of proposed storage. Typically, storage is most economically obtained with embankments across natural or man-made drainage swales.

Lutey, T. 2001. Coalbed methane regulatory battle will be fought over water. Bozeman Daily Chronicle, Nov. 16, 2001.

Concerns of the Northern Plains Resource Council (NPRC), Montana's strongest organized opponent to CBM development, are highlighted in this recent newspaper account. One of NPRC's main concerns about CBM drilling is the water discharged to land surfaces. This concern hinges on the quantity of water pumped and the possible influence on wells of nearby landowners. NPRC points out that CBM drillers are generally exempt from state water rights laws that normally allow senior water right holders to protect their claim. The Council suggests a requirement for 'beneficial water use permits' that would give persons with existing water rights a legal position. In 2001 the Montana legislature excluded CBM discharge water from the state's wastewater definition. NPRC hypothesizes that if the large quantities of CBM discharge water are not considered wastewater then they must be beneficial. According to the Montana Department of Natural Resources and Conservation no one has filed a water rights complaint against a CBM operator in southeast Montana, where all but a few CBM wells are on hold while four law suits filed by NPRC are decided.

Lyons, P.C. 1996. Coalbed methane potential in the Appalachian states of Pennsylvania, West Virginia, Maryland, Ohio, Virginia, Kentucky, and Tennessee – an overview. Legal, economic, and environmental constraints. USGS, Energy Resources Team. Open File Rep. 96-735. 4 p.

Legal conflicts have arisen among surface owners, owners of coal rights, and owners of oil and gas rights. In 1977, Virginia enacted a statute that all migratory gases are the property of the coal owner rather than the gas lessee or surface owner. However, in Pennsylvania methane ownership was considered to be part of the coal rights, but the surface owner retained rights to propane that migrated from the coalbed. Such migrated coalbed methane can be significant because most of the thermogenic methane generated in coal has probably migrated out of the coal to be trapped in tight sands of surrounding strata or has escaped to the surface. The author notes that water is an important economic and environmental factor in CBM projects. Water disposal techniques include well injection and discharge into surface streams. Injection wells are the preferred method of disposal in the central Appalachian Basin, whereas discharge into surface streams, after treatment in ponds to meet water quality regulations, is a common disposal method in the Black Warrior Basin. Total dissolved solids from CBM wells in the central Appalachian Basin have been reported as high as 30,000 ppm compared with 3,000 ppm for the Black Warrior Basin.

McBeth, I. H.; Reddy, K. J.; Skinner, Q. D. 2001. Quality of coalbed methane product water: arsenic, boron, fluoride, and selenium. *In* J.J. Warwick, editor. Water Quality Monitoring and Modeling. Annual Spring Specialty Conf., American Water Resources Assoc., April 30-May 2, 2001, San Antonio, TX. The Association, Middleburg, VA. pp. 259-264.

In the Powder River Basin, many of the early studies on quality of CBM water were based on samples from the coalbed aquifer system. The authors suggest that further information is needed for water quality at the discharge points and in disposal ponds. This project focused on the trace elements, arsenic, boron, selenium, and fluoride because of their known potential problems in soil, plants, and water environments. CBM produced water from 14 sites was examined at discharge points and after it had reached steady state conditions with local soils in holding ponds. The goal was to examine how quality of produced water changes as it reacts with soil surrounding the pond area. The pH of discharge water ranged from 6.86-7.39 and corresponding disposal pond water pH was 7.29-8.16. This suggests that CBM product water in the disposal ponds reaches equilibrium with the calcium carbonate system that typically buffers pH between 7 and 8. In general, arsenic and selenium concentrations in disposal ponds showed an increase over values at the point of discharge. Boron concentrations showed a decrease in disposal ponds, whereas fluoride concentrations remained the same between discharge points and ponds. The concentrations of trace elements in this study were below the EPA human drinking water limits for both CBM water discharge points and corresponding disposal ponds.

McCune, D. 2000. TORP [Tertiary Oil Recovery Project] developing new coalbed methane manual. PTTC (Petroleum Technology Transfer Council) News 2nd Quarter 2000. 1 p.

The Tertiary Oil Recovery Project at the University of Kansas is compiling a CBM manual for those interested in this relatively new industry. Dwayne McCune, a Kansas consulting petroleum engineer and associate of TORP, University of Kansas, and the Petroleum Technology Transfer Council, is the author. Primary focus of the publication is on drilling, completion, and operational matters, with emphasis on the Midcontinent CBM fields. Separate chapters will address testing, coal characteristics, determination of methane reserves, and environmental and regulatory concerns. At the time of this annotation coast and date of publication could not be confirmed.

McGarry, D.E. 2000. Challenges in assessment, management, and development of coalbed methane resources in the Powder River Basin, Wyoming. *In* Proc. 25th Intern. Tech. Conf. on Coal Utilization and Fuel Systems. pp. 709-720.

The author, representing the Wyoming Reservoir Management Group of the BLM, indicates that limited pipeline capacities, environmental studies, and legal issues have constrained CBM development in the Powder River Basin, and suggests that development and production would have outpaced even the current rapid expansion if these constraints had not existed. As long as economics are favorable, continued expansion of CBM activity are expected as these issues are resolved.

- Two principal advances allowed CBM production to become economic in the Powder River Basin. First, it was determined that effective dewatering of coal seams required more closely spaced wells than were initially used. Early CBM wells were drilled on 160 acre or larger spacing patterns. At present in the Wyodak CBM development area, wells are drilled on 40 or 80-acre spacing patterns.
- Second, improved well completion procedures in recent years have also been an important factor allowing CBM development. Conventional completion methods, involving casing and perforating the coal seams, did not promote efficient gas desorption. Also, the acid treatments used to stimulate production might actually have damaged the coals and inhibited methane production. The current well completion procedure is to set well casing to the top of the coal, then under-ream the coal to a larger diameter than the drilled hole, exposing more surface area for gas desorption. The only treatment procedure now used, if any, is water injection to fracture the coal and improve permeability.
- The drilling and completion practices that have evolved allow rapid and effective recovery of CBM reserves. Wells are now normally drilled and produced in groups or 'pods' to accomplish initial dewatering as quickly as possible. Operators have found that by targeting small structural highs in the coals the pod approach enhances effectiveness of dewatering and gas desorption.
- Drilling and completion costs for wells ranging from several hundred to 1,000 feet deep are approximately $25,000 per well, and gathering and other facility costs are about $30,000 per well. As a result of these low development costs, CBM wells can be produced economically at much lower production rates than required for conventional gas reservoirs.
- Several generations of environmental and land-management planning studies have been prepared to address Powder River Basin CBM development. The author contends that all of these studies used inaccurate gas content measurements, with the result that CBM activity forecasts based on these data have underestimated the actual levels of development by substantial margins.
- Environmental review is required before drilling can be approved on federal leases. Similar reviews are not required for non-federal lands. This causes drilling on federal leases to be curtailed while CBM development of state and private lands continues. This creates a risk for loss or damage to the federally administered CBM resources.
- The resulting disparity in CBM development patterns has created the potential for drainage of methane from the federal leases that are near areas of CBM development

on state or private land. Quantitative evaluation of methane drainage from specific leases is not presently feasible because of inadequate reservoir data.

- In the Powder River Basin, CBM development is occurring close to large active coalmines. With coal and oil and gas leases occupying the same lands, conflicts between the two resources are inevitable. Conflicts between CBM development relate to two issues: one is the effect of coal mining on the CBM resource, and the other involves direct interference with development of one resource by the other.
- It is widely believed that coal dewatering by the mines has caused depletion of CBM resources, but the presence and nature of this depletion is uncertain. Prior to early 2000, no data were available to document the extent of CBM depletion by coal mining. Some CBM operators are now collecting data to address this issue. Dewatering coal seams for CBM development creates concerns about removal of large quantities of water from principal aquifers in a relatively arid region. At present, there are substantive plans for conservation of the water resource. The present practice is to move produced water into retention ponds or into existing, normally dry, drainages.
- The author records several additional water-related concerns including increased soil erosion, permanent damage to coal seam aquifers, and subsidence.
- Studies are currently in progress to evaluate carbon dioxide injection into Powder River Basin coal seams as a means of greenhouse gas sequestration.
- In the Powder River Basin accelerating CBM development coupled with inadequate technical information have created challenges in resource assessment and management. Proper data acquisition in the early stages of CBM development would have reduced these challenges. The author prepared this guide to assist others facing similar challenges.

Masszi, D.G.; Kahil, A.A. 1982. Coal demethanation principles and field experience. J. Can. Pet. Tech. 21(4):75-78.

Noval Technologies Ltd. initiated a program in Alberta in 1976 to develop coal demethanation technology and demonstrate its economic viability. After five years of evaluation, Noval believed that coal demethanation techniques were sufficiently advanced to make commercial projects feasible. Some conclusions by the author were:

- Gas content of coal is affected by rank, depth of burial, type of coal, permeability of coal to gas (which in turn is affected by groundwater conditions and density and frequency of fractures), permeability of surrounding lithology to water and gas, tectonic history of the area, and permeability of coal to water.
- To initiate desorption of methane in the coalbed, the equilibrium of the coal/gas system must be disturbed in a manner that the coal will be able to retain less gas. The easiest way to accomplish this is to reduce hydrostatic pressure on the coal by removing groundwater.
- Groundwater conditions in the area have a great influence on gas production and lowering of the water table can be a major problem.
- The main parameters for evaluating potential for CBM production are gas content of coal, coal thickness, permeability to gas and water, formation pressures, and groundwater level.

- Groundwater studies should be undertaken in an area of interest to design the most effective dewatering system.
- Water well measurements should be incorporated into the CBM well design because it is the water level in the well that is the important factor, not the flow rate that was initially measured.
- It is impossible or very difficult to dewater a significant amount of a coal seam with one well.

Mastalerz, M.; Glikson, M.; Golding, S.D., editors. 1999. Coalbed methane: scientific, environmental and economic evaluation. Kluwer Academic, Dordrecht, Neth. 592 p.

This special publication on coalbed gas is multidisciplinary in scope and covers a wide range of topics including exploration, production, resource calculations, emissions, and regulatory processes. Despite the reference to environmental evaluation in the text's title, the volume provides no information on water handling, environmental, or land-use aspects of CBM development. The only article annotated from the collection of papers, many of which focused on Australia, is the Canadian paper by F.M., Dawson on hydrogeologic aspects of CBM exploration in structurally complex terrain.

Mavor, M.; Pratt, T.; DeBruyn, R. 1999. Study quantifies Powder River coal seam properties. Oil and Gas J. 97(17):35-40.

Although water production rates can be high, Wyoming allows the very fresh produced water to be discharged into ponds and drainages, greatly improving production economics of CBM production. Many ranchers welcome the additional water supply from CBM operations because the region has an arid climate.

Merschat, W.R. 1999. Coalbed methane: gas boom, environmental bust. Casper Star-Tribune, 29 Aug., 1999. Reprinted on Powder River Basin Resource Council website.

The author, a geologist and principal of Scientific Geochemical Services, recorded his observations and concerns about CBM development in the Powder River Basin, as summarized below.

- CBM water produced in the Powder River Basin is potable and will be stored on the surface or dumped into drainage systems. The author expects that groundwater levels will be lowered and some water wells will be lost.
- Dewatering may permanently damage aquifers in the basin. Dewatering lowers groundwater levels on a regional basis. If the structural integrity of aquifers remains unchanged, then aquifer recharge is possible, but this may take up to 200 years.
- Ducks, fish, and vegetation that will benefit from ponds created for CBM storage will suddenly lose this benefit when CBM extraction ends in a few years.
- The author has measured elevated levels of methane in soil near CBM operations in the basin and suspects that levels of methane will increase with increased dewatering activity.
- At the time of this article there were 5 underground coal fires burning in the San Juan Basin of Colorado. One fire had been burning for many years while the other four were new, the result of spontaneous combustion. The new fires are located

along the edge of coal where dewatering has lowered the groundwater. Powder River Basin coal is low rank bituminous, which the author suggests is relatively susceptible to spontaneous combustion. For example, during the recent past, fires burned large amounts of coal in the Powder River Basin leaving over 1600 mi^2 of clinker (red ash-like baked rocks). The author believes that the Powder River Basin coal is more susceptible to spontaneous combustion than the San Juan Basin coal because in Wyoming dewatering of horizontal coal seams would expose more coal to oxygen than in the San Juan Basin where coal seams are angled from horizontal.

Meyer, J. 2000. Coalbed methane produced water – Belle Fourche River Basin 1993 to 1999. Geol. Soc. Am. Annu. Mtg., Nov. 2000, Reno, NV. U.S. Dept. Int., Bur. Land Manage. 11p.

CBM production in Wyoming usually involves surface discharge of produced water. A major question with discharge of this water is the volume of water lost to evapotranspiration and infiltration. In the past, assumptions were made about the rate of infiltration along stream channels, and in the case of the Wyodak environmental impact statement it was assumed that produced water volumes were reduced at the rate of about 1% per mile of channel. Since 1997 a sufficient number of producing CBM wells were completed to allow comparison of CBM water production rates with measured streamflow volumes. The author, a soil scientist-hydrologist with BLM, analyzed data from a portion of the Belle Fourche River in the months of May-September inclusive, 1999. Produced water volumes had increased substantially since the onset of CBM production. For example, in Caballo Creek there were only four CBM wells in July 1993 that produced 1.3 acre-feet of water in that month. By September 1999 there were 263 producing wells accounting for 343 acre-feet of water during that month. Average pumping rate per well reached a maximum in the Caballo Creek drainage in June 1998, at 16.5 gal/min/well. By September 199 the average pumping rate in Caballo Creek had decreased to 9.8 gal/min/well. Streamflow volumes show little or no correlation to these increases in volume of CBM produced water. The author concluded that little or none of the water discharged from CBM operations was reaching stream gauge locations. During periods with little or no precipitation, evapotranspiration and infiltration losses of produced water may be greater than 90%. Evapotranspiration and infiltration losses are dependent on local conditions such as geology, topography, vegetation, impoundments, and water management practices. Rates of these losses vary from basin to basin and caution must be used in assuming area-wide relationships. In the case described here, actual volumes of produced water and predicted streamflows were far below those estimated in the environmental impact assessment. Not only were produced water volumes less than predicted but streamflow conveyance losses were significantly greater than predicted.

Meyer, J. 2000. Infiltration/evaporation of CBM produced water from a reservoir site. Geol. Soc. Am. Annu. Mtg., Nov. 2000, Reno, NV. U.S. Dept. Int., Bur. Land Manage. 6 p.

One question with discharge of CBM water is the volume of water lost to evapotranspiration and infiltration. The author has examined this question both in stream channels and in reservoirs. In the Brown Reservoir in Wyoming, water from 8 producing

CBM wells is piped directly into the reservoir. When filled to the outlet, the reservoir impounds over 45 acre-feet of water and covers about 6 surface acres. CBM water was produced from September 1999 to August 2000 and discharged into the reservoir. BLM, in cooperation with the CBM producer and landowner, installed monitoring equipment to measure changes in shallow groundwater levels and also outflow of produced water from the reservoir. No increased groundwater was detected in the test wells. Estimated infiltration losses remained relatively constant throughout the year, with loss rates varying from 12.9 to 14.8 acre-feet per month. Instantaneous measurements of discharge at the reservoir outlet indicated that most of this loss occurred through the reservoir, and not along the channel between the outlet and the flume.

Miyamoto, T. 2001. Methane means big bucks to state. Univ. Wyoming, Communications Dept., Laramie, WY. 3 p.
The following CBM-related environmental concerns are mentioned in this University of Wyoming website extension note:

- Wyoming ranchers are concerned that CBM drilling on their land is polluting their water and costing them money.
- There is surface damage in some areas as well as soil erosion after vegetation is destroyed by traffic.
- A primary concern is that CBM development is happening so rapidly and intensely, with so many wells being developed at the same time, that there is a large amount of water being dumped on the surface in a short time.
- According to the Wyoming Department of Environmental Quality, Wyoming's 30 to 40 trillion ft^3 obtainable methane is only enough to meet the nation's gas needs for 18 months but if it were extracted gradually CBM wells could be active in Wyoming for several decades. Thus, the issue is whether it is possible to balance production rates and environmental concerns so that Wyoming can take advantage of economic benefits of CBM production but also preserve landscape, water, and air quality.

Montana Department of Natural Resources and Conservation. 1999. Appendix E. Final order in the matter of the designation of the Powder River Basin controlled groundwater area. Oil & Gas EIS Amendment of the Powder River and Billings RMPs, Water Resources Technical Report. 11 p.
Montana's Water Source Mitigation Contract in the Final Order cited above specifies that "Coalbed methane operators must offer water mitigation agreements to owners of water wells or natural springs within one-half mile of a CBM field proposed for approval by the Board … The mitigation agreement must provide for prompt supplementation or replacement of water from any natural spring or water well adversely affected by the CBM project". The Final Order also specifies "Hydrologic conditions in the targeted coalbeds must be assessed prior to field development to establish baseline conditions. Specific requirements of the field rules will dictate that groundwater pressure is monitored in appropriate locations using dedicated monitoring wells. … Dedicated groundwater monitoring wells must be placed in the next aquifer above and below the targeted coal seam, if applicable, within the production field. Also, as a minimum requirement, at least one 24-hour aquifer test must be conducted using at least one

observation well, and baseline groundwater pressures and water quality data must be obtained from the monitoring wells prior to production".

The Final Order indicated that management of the controlled groundwater area should involve a technical advisory committee with expertise in coal aquifer hydrology, hydrogeology, shallow groundwater systems, water quality, and CBM extraction systems and operations. In a memorandum summarizing public concern it states "The public comment was unanimous in its concern that scarce water resources and existing water uses in the area be protected and overwhelmingly favored establishing a controlled groundwater area". In the Final Order for the designation of such a controlled groundwater area, the following findings of fact dealt with environmental concerns about aquifers:

- CBM extraction technology requires groundwater withdrawal to lower groundwater levels and to reduce water pressures in the coalbeds. Wells may be placed at regular intervals over large areas covering many square miles. The wells are pumped continuously with the specific intent of lowering water pressures in the coalbed. Lowering water pressures will lower water levels in the aquifer;
- During CBM development the intent is to remove water only from coal aquifers. Other aquifers in an area of CBM development may or may not be affected depending on connections between aquifers;
- Coalbeds are important regional aquifers in water-scarce southeastern Montana. The coal aquifers are often the only practical source of fresh water for domestic stock and agricultural uses by people in the area;
- Since CBM development has limited duration, 20 to 30 years, in any particular field, and because the aquifer is not otherwise disturbed, water in the aquifer most likely will recover to its pre-development level. However, even if an aquifer were to recover rapidly after development, the long period of development could cause severe hardship to local water users. Moreover, interrelationships among aquifers along with future precipitation patterns could cause unpredictable results;
- Montana's Department of Natural Resources and Conservation usually considers a one-half mile (0.8 km) radius from any particular water well as the zone of possible influence from the well;
- Water drilled for CBM development could in some cases be developed as water sources for local residents, agriculture, and businesses that can use such water;
- CBM wells that are inadequately sealed may contaminate water in one aquifer with poor quality water from another aquifer and may also introduce methane into non-coal aquifers.

Montana Farm Bureau Federation. 2001. Coal bed methane marks tough issue for agriculture. Montana Farm Bureau Federation, Lewiston, MT. 1 p.

CBM development is a concern for many landowners in southeastern Montana and in 2001 there were three bills before the state legislature dealing with CBM issues.

- Bill HJR-27 requested that the Montana Environmental Quality Council provide oversight for preparation of an environmental impact statement regarding CBM development.

- Bill HB-572 would create a Coal Bed Methane Protection Act to provide compensation to landowners and water rights holders for damage caused by CBM development.
- Bill HB-573 would authorize the Board of Oil and Gas to permit CBM wells in a way that protects the private property rights of the owners of the mineral reserves.

The article noted that discharge of groundwater must be managed for use as irrigation or livestock water, or other beneficial uses. If the use of discharged groundwater is not economically feasible, the water can then be reinjected to acceptable subsurface strata, discharged to the surface subject to permit requirements or managed through other disposal methods. This proposed legislation was to become effective in June 2002 after the current environmental impact statement is completed in May 2002.

Montana State University. 2001. MSU team assesses pros and cons of methane production. Montana State Univ., Bozeman, MT. MSU News. 3 p.
The following points are emphasized in this Montana State University extension note:

- Since agricultural land will be needed long after the estimated 20-year life of methane production, maintaining health of the soil is of major economic importance in southeast Montana.
- Sodium compounds create a complicated soil chemistry situation. In some cases, produced water may have sodium levels that leave the water safe for people to drink but may still damage the soil.
- Sodium-rich water can be managed but there is not yet sufficient information to do so for the range of soil types where CBM development may occur.
- J. Bauder, Montana State University, is working with landowners, Montana Conservation Districts, EPA, BLM, USDA, and the Northern Cheyenne Reservation, to develop guidelines for land managers to use in defining what water quality criteria should be specified in CBM drilling contracts. Results of this work are expected to be available in two years.

Montgomery, S.L. 1999. Powder River Basin, Wyoming: an expanding coalbed methane (CBM) play. AAPG Bull. 83(8):1207-1222.
Disposal of produced water is not discussed in this article, but the report demonstrates the wide variability in amount of dewatering needed for CBM production. Coalbeds are not uniform in hydrological character but change from being partly to largely dewatered in updip areas near existing mines to high permeability, overpressured aquifers in downdip areas. Thus, updip wells require little or no dewatering for gas production, whereas downdip wells produce larger volumes of water than expected and often cannot be sufficiently dewatered when drilled on fairly wide spacing (e.g., one well per 64 ha). Also, CBM production wells that lie close to existing mines may have little produced water because earlier mining already resulted in some dewatering.

Morrison, J.; Malone, G.; Phinney, C., editors. 2001. Coalbed Methane Monitor [Several articles.] Powder River Basin Resource Council, Sheridan, WY. 39 p.
The Powder River Basin Resources Council website (http://www.powderriverbasin.org/prbrc/cbm_monitor_page1.htm) contains several articles by different authors that

reflect observations, opinions, and concerns of public interests in Wyoming. The information on this website is too detailed to annotate effectively. The following titles of articles indicate the range of subjects addressed in this Coalbed Methane Monitor: CBM Industry Demands More Electricity to Produce Gas; Stand Up for the Powder River; Dispelling CBM Myths; Noisy Compressors Shatter Solitude; What Are We Doing to Wyoming?; Water, a Basic and Valuable Resource; Is Industry a Good Neighbor?; One Bad Apple; Montana and Wyoming Wrangle Over CBM Discharges; Ranch Couple Fight to Protect Land; Water and Soil Studies Initiated to Protect Ranch; Negotiating Ups and Downs; Worker Injuries, Deaths Haunt CBM; Split Estate Issue Prompts Need For Reform of Oil and Gas Laws; Report Confirms Possible Methane Seeps and Subsidence; CBM Discharge Water Wreaks Havoc Downstream; Studies Lagging on CBM Discharge Impacts; and Experts Address CBM Water and Soil Interactions.

Morton, P.A. 2001. Testimony of Peter A. Morton, on behalf of the Wilderness Society before the Subcommittee on Forests and Public Land Management, Committee on Energy and Natural Resources, United States Senate, April 26, 2001. The Wilderness Society, Wash., D.C. 12 p.

The author's testimony referred to several cumulative effects of the infrastructure of drill sites, pipelines, and roads associated with oil and gas development, including CBM extraction, with the suggestion that the major uncounted environmental cost is associated with produced water. The author's key points were:

- "Greatly increased drilling activity for coalbed methane is having profound real-life impacts on many families and communities in the West."
- "To release the methane gas from coalbeds, enormous amounts of groundwater must be pumped from coal aquifers to the surface. The water discharged on the surface comes from shallow and deep aquifers containing saline-sodic water. The total amount of water produced from individual coalbed gas wells is generally much higher than that from other types of oil and gas wells."
- "Water disposal can vary from inexpensive methods, such as discharge into streams, to more costly alternatives such as underground injection and surface discharge after water treatment."
- "Dewatering of deep aquifers may upset the hydrologic balance, eliminating or reducing the availability of this water for future agricultural and domestic uses, as well as recharge for shallow aquifers and surface water."
- "The discharge of groundwater can deplete freshwater aquifers, lower the water table, and dry up the drinking water wells of homeowners and agricultural users."
- "The short-term economic costs include drilling new, deeper wells for current and future homeowners, ranchers, and farmers, assuming successful wells can be found."
- "If the freshwater aquifers do not fully recharge, the long-term economic costs to affected landowners, homeowners, communities, and states across the West could be severe, including the foregone opportunity (option value) to use aquifer water in the future."

Mount, D.R.; O'Neil, P.E.; Evans, J.M. 1993. Discharge of coalbed produced water to surface waters – assessing, predicting, and preventing ecological effects. Quart. Rev. Methane From Coal Seams Technology 11(2):18-25.

In the 1980s, the Environmental Protection Agency required establishment of chemical-specific effluent limitations, biological monitoring through whole-effluent toxicity testing and assessment of affected instream communities. At the same time the Gas Research Institute began a program in the Black Warrior Basin to assess how these EPA proposal could be met. Several general conclusions can be drawn from the GRI research:

- Evidence from all studies shows that CBM waters can be discharged into surface waters without adverse environmental effects, provided that the discharges are properly managed and monitored.
- Studies at the Cedar Cove CBM field in Alabama indicate adverse effects on instream communities when chloride concentrations exceed 565 mg/L. EPA's Ambient Water Quality Criterion defines 230 mg/L chloride as protective of instream communities.
- Laboratory toxicity tests on standard test organisms correlate well with results of instream studies, suggesting that such tests can be used to predict instream effects of produced water discharge.
- The toxicity of total dissolved solids is dependent not on total ion concentrations but on the specific ionic composition (especially chloride and sulfate) of the produced water.
- A survey across the Black Warrior Basin suggests that toxicity of CBM waters is related to major ion composition and not to trace contaminants.
- The Cedar Cove model described by the authors provides a comprehensive approach for assessing the environmental acceptability of produced water discharge.

Mullins, G.L.; Hajek, B.F. 1998. Effects of coalbed methane-produced water on sorghum-sudangrass growth and soil chemical properties. Commun. Soil Sci. Plant Anal. 29(15/16):2365-2381.

Since land application is a potential method for disposal of CBM produced water, a greenhouse study was conducted to evaluate plant responses and changes to chemical properties of a northern Alabama soil. Results from this preliminary short-term study showed that CBM produced water typical for Alabama (total dissolved solids less than 2,000 mg/L) can be applied to highly weathered soils. The results indicate that plant growth of summer annual grasses will be optimized if an irrigation system is used to apply produced water at a rate to maintain soil moisture at or near field capacity.

Nuccio, V. 2000. Coal-bed methane: potential and concerns. U.S. Geol. Surv. Fact Sheet FS-123-00. 2 p.

The author suggests that scientific understanding of coalbed methane is in the early learning stages, partly because few models are available for planning development of CBM resources on a broad scale. Studies now underway by the U.S. Geological Survey are designed to develop such models. Some highlights of this Fact Sheet include:

- Because coal has such a large internal surface area, it can store large volumes of methane, six or seven times as much gas as a conventional natural gas reservoir of equal volume.
- Increased CBM production has technological and environmental difficulties and costs. For example, in a conventional oil and gas reservoir, gas lies on top of oil that, in turn, lies on top of water. An oil or gas well can extract the petroleum without

producing a large volume of water. In contrast, water permeates coalbeds and to produce methane this water must be drawn off first.

- This produced water, commonly saline but in some areas potable, must be disposed in an environmentally acceptable manner. Surface disposal can affect streams and other habitats, and subsurface reinjection can be costly.
- In some cases the produced water is allowed to flow into surface drainages or is placed in evaporation ponds. In cold regions, it is possible to freeze the water, collect the salts that separate out, and dispose of or use them independently of the water, which can be discharged.
- In some areas, methane may have contaminated groundwater sources and methane may have migrated into residential neighborhoods. However, the controls on methane migration are not well understood. Some contamination may come from migration of methane along natural fractures and some may come from older gas wells that tapped reservoirs in sandstones associated with the coals. Also, some methane migration may be the result of new CBM wells. In some locations this has now become a problem because of new residential development near methane migration pathways.
- The author emphasizes that burning methane adds considerably less carbon dioxide to the atmosphere than burning coal, and production of methane from coal prior to mining reduces the amount of methane released to the atmosphere during the mining process.

O'Hayre, A. 2001. Current CBM discharge contributions to main stem streams, Powder River Basin, Wyoming. Report prepared for Petroleum Assoc. of Wyoming, Casper, WY. 3 p.

Applied Hydrology Associates Inc., in this report to the Petroleum Association of Wyoming, provided estimates of conveyance loss along stream channels for CBM water released into various drainage basins in Wyoming. The author noted that the predicted increased flows in mainstem streams were over estimated in the Wyodak environmental impact statement primarily because the water lost to infiltration and evapotranspiration was underestimated. Flow measurements from stream monitoring stations and instantaneous flow measurements along tributary channels downstream of CBM discharges showed that very little of the discharged water reached the main stem streams. It is thought that the measured reservoir and channel conveyance loss is mainly re-infiltration as evaporation rates were low when the field studies were done in October. Most of the water re-infiltrated along minor tributary channels and in swales or surface water impoundments located downstream of the discharge points.

Oil and Gas Accountability Project. 2001. Western coalbed methane project. OGAP, Durango, CO. 4 p.

Ten NGOs from several western states have established the Western Coalbed Methane Project to aggressively challenge CBM development in their region. Participating groups are: Oil and Gas Accountability Project (coordinator of the project), Native Action, Northern Plains Resource Council, Powder River Basin Resource Council, San Juan Citizens Alliance, Southern Colorado CURE, South Ute Grassroots Organization, Southern Utah Wilderness Alliance, Western Colorado Congress, and Wyoming Outdoor

Council. This coalition believes that regions of Colorado, Montana, New Mexico, Utah, and Wyoming are “serving as America’s guinea pigs for the experimental development of coalbed methane”. The stated objectives of the Western Coalbed Methane Project’s campaign are “to ensure that CBM development proceeds only when surface and groundwater are protected and when the cumulative impacts of thousands of CBM wells, roads, pipelines, hydraulic fracturing procedures, and water disposal wells are understood”. The campaign’s concerns are stated as follows:

- “In order to produce methane from coal seams, massive amounts of groundwater must be pumped from underground aquifers, coal seams are fractured with toxic fluids to stimulate production, and a web of roads and pipelines are constructed to deliver the product to market”;
- “Thousands of wells and roads have scarred the landscape, denuded wildlife habitat, contaminated drinking water, and methane and hydrogen sulfide seeps have forced some families from their homes. Domestic and stock wells have dried up and billions of barrels of produced water (often high in sodium, arsenic, and other contaminants) are being dumped on the surface and into rivers. Underground coal fires are the latest problem among a laundry list of devastating impacts.”
- The Western Coalbed Methane Project noted that efforts have forced companies “to stop illegally dumping produced water in rivers, irrigation ditches, and spreading it on roads for dust control. Produced water, often containing toxic and hazardous chemicals, has also been found to contain benzene and toluene, known carcinogens”.

Oil and Gas Journal. 1999. Unocal targets coalbed methane resource north of Anchorage. Oil & Gas J. 97(36):44, 48, 51.

This article emphasizes that safe water disposal concerns are uppermost in the mind of any CBM well operator, because CBM wells commonly produce large quantities of water. It is especially critical to identify the entire stratigraphic section containing all of the potential fresh water aquifers to design safe cementing and casing programs for both producing and disposal wells in order to protect fresh water supplies. Alaska regulations require that application for a fresh water aquifer exemption is required if the potential disposal zones contain fluids with total dissolved solids in the range of 3,000-10,000 ppm.

Oil and Gas Journal. 2000. Infill drilling land use issues heat in SW Colorado. Oil & Gas J. 98(26):39.

Applications for infill CBM drilling in the Ignacio-Blanco Gas Field raised several land use issues in southwestern Colorado. Operators want the state to allow spacing down to one well per 65 ha from 130 ha to encourage development of methane from Cretaceous Second Fruitland coal in the San Juan Basin. Among the infill drilling issues is a concern expressed by a pediatrician that noise from gas wells near residences can cause stress and increased illnesses, particularly because residents have no control over noise from CBM well sites. Industry’s response is that they have offered to enter into a voluntary plan to mitigate impacts. The plan includes testing for methane contamination in the one water well closest to the infill gas well, monitoring the Fruitland Formation for methane seeps, testing old gas wells that have been plugged, and complying with state and federal noise, water, and air quality laws. Other mitigative measures include alternative well pumps that are smaller and less visible, keeping well sites small, using existing well sites and roads, helping to maintain country roads, and directional drilling when circumstances allow.

Oldaker, P. 1995. Domestic well sampling results prior to Amoco's coal bed methane development in the central Raton Basin. *In* R.M. Graves and S.J. Thompson, editors. Proc. 1995 Rocky Mountain Symposium on Environmental Issues in Oil and Gas Operations – Practical Solutions for the '90's, Oct. 16-18, Golden, CO. M. Francisco and J. Proud, Proc. editors. Colorado Schl. Mines, Golden, CO. pp. 321-333.

The author, a consulting hydrogeologist, was contracted by Amoco Production Company (U.S.A.) to sample 29 domestic water wells and three surface water sites prior to development of a CBM project in Colorado's Raton Basin. Wells were completed in Quaternary alluvium and in the coal-bearing Raton Formation. Twelve samples showed oxidation characteristics of mixed cation and bicarbonate-sulfate water types generally associated with the alluvium and surface water. The domestic water wells were divided into oxidation, reduction, and borderline groups based on sulfate and sodium ion percentages. Surface and alluvial water samples made up the oxidation group with a mixed cation and bicarbonate-sulfate water type, Bedrock water samples made up the reduction group with a sodium cation and bicarbonate water type. Fifteen samples showed reduction characteristics of the sodium-bicarbonate water type associated with both bedrock formations. Dissolved methane was found in all samples of the reduced group as shallow as 60 ft. Samples of three wells showed isotopic ratios that indicated a thermogenic origin. High percentages of bacteria that were found appear to be the main cause of taste and odor problems in the waters sampled.

O'Neil, P.E. 1994. A review of water-quality, biological risk, and discharge monitoring studies relative to the surface disposal of produced waters from the development of coal-seam methane in Alabama. Geol. Surv. Alabama, Tuscaloosa, AL. Circ. 177. 36 p.

One of the primary environmental concerns with CBM development is disposal of produced water. This water is typically less saline than seawater but nonetheless poses significant biological risk if managed and disposed improperly. The Gas Research Institute sponsored studies from 1985 through 1993 in the Black Warrior Basin to address environmental issues related to disposal of CBM water. This review consolidates information that had been published up to 1994, with P.E. O'Neil generally as senior author. This report contains an extensive literature review and presents a summary table of specific topics covered in each of 21 scientific studies related to environmental effects of CBM produced waters.

- These studies demonstrated that CBM produced waters can be safely disposed if the wastewater treatment and disposal processes are properly managed and monitored. The water quality criterion for chloride, 230 mg/L, was demonstrated to be protective of aquatic systems, and instream biological effects occurred only when chloride exceeded 565 mg/L instream.
- Standard aquatic-toxicity tests for *Ceriodaphnia dubia* demonstrated that chronic toxicity effects occurred from 600 to 900 mg/L chloride.

- The Cedar Cove monitoring approach outlined in this report is effective at maintaining control over discharged effluents within the regulatory guidelines by allowing CBM producers to use the assimilative capacity of receiving streams.
- Determining whether the biological integrity of receiving streams has been impaired can be difficult, but in the future will probably be a step required in discharge permit compliance and environmental risk assessment.
- In Alabama, discharge permits for CBM water are written on the basis of either: chemical or parameter-specific criteria that are not to be exceeded; or on the basis of mass quantities of material that may be discharged over specific time periods. Permits written for streams typically have criteria-specific requirements while permits for larger rivers are usually on a mass discharge basis.
- Chemical-specific criteria are usually written as follows: dissolved oxygen (>5.0 mg/L); pH (6.0-9.0); total dissolved iron (3.0 mg/L monthly or daily average, 6.0 mg/L maximum); total dissolved manganese (2.0 mg/L monthly or daily average, 4.0 mg/L maximum); biochemical oxygen demand (30 mg/L monthly or daily average, 45 mg/L maximum); and dissolved chloride (230 mg/L monthly or daily average, 860 mg/L maximum).
- Although discharge limits are usually written using the 230 mg/L chloride limit, operators typically implement discharge controls when chloride reaches a concentration between 150 and 200 mg/L.
- Toxicity testing requirements are written into all NPDES permits. Test species and type of test are determined by specifications in discharge permits. Generally, chronic toxicity tests are required for effluents discharged into streams while acute toxicity tests are require for effluents discharged into larger rivers and reservoirs.
- Two models were developed to predict change in community structure of benthic macroinvertebrates. The abundance model predicted percent decline in log density of macroinvertebrate communities with increasing chloride concentrations. The taxa model predicted percent decline in number of macroinvertebrate taxa with increasing chloride concentration.
- Instream biomonitoring indicated that: benthic macroinvertebrate and fish populations could be used to assess biological integrity of streams receiving CBM water and surface mine runoff; in general, streams receiving coal surface mine runoff had fewer species and lower density of macroinvertebrates compared to streams not receiving mine runoff and, at the quantities released, CBM waters appeared not to contribute additional stress to the fauna in streams already impacted by coal surface mine runoff; during three years of continual CBM water discharge no significant long-term effects were observed in diversity or abundance of either benthic macroinvertebrates or fish; and increased discharge of organic matter (primarily algae) from settling lagoons appeared to increase secondary productivity of macroinvertebrates downstream of CBM produced water discharges.
- Too detailed to reproduce here, Table 5 of the author's report lists specifications for conducting instream bioassessment, with recommendations on how to sample for water quality, continual water quality monitoring, instream bioassessment, and aquatic toxicity testing. Specifications are provided for criteria such as: tests to be conducted, length of tests; season to be conducted; sampling frequency; locations of

collection points; parameters to be measured; location and depth of probes; and numbers of replicates.
- The information developed by the Gas Research Institute, Geological Survey of Alabama, and other collaborators has been a significant factor in development of Alabama's CBM resource. Studies of CBM produced waters have shown crucial links between regulatory mechanisms, wastewater treatment processes, and biological monitoring methods.

O'Neil, P.E.; Harris, S.C.; Mettee, M.F. 1989. Stream monitoring of coalbed methane produced water from the Cedar Cove degasification field, Alabama. *In* 1989 Coalbed Methane Symp., Tuscaloosa, AL. Univ. Alabama, Tuscaloosa, AL. pp. 355-361.

In Alabama, CBM produced waters are disposed either through land application or stream discharge. This study developed concentration-response models that describe the effects of chloride on benthic invertebrate community structure. These models were used to calculate an instream chronic value of about 593mg/L chloride. At less than this concentration, little significant impact to aquatic communities is expected, but prolonged exposure above this concentration would likely result in significant adverse changes in biological community structure. Long-term monitoring of faunal communities in a stream receiving continuous discharge of produced waters lower in chloride than the calculated chronic value (593 mg/L) revealed no significant changes in the community structure of fishes or benthic invertebrates. Additionally, measures of growth and reproduction of two indigenous fish species were not significantly affected by discharge of the low-level chloride water.

O'Neil, P.E.; Harris, S.C.; Mettee, M.F.; Shepard, T.E.; McGregor, S.W. 1993. Surface discharge of wastewaters from the production of methane from coal seams in Alabama, the Cedar Cove model. Geol. Surv. Alabama, Tuscaloosa, AL. Bull. 155. 259 p.

The most significant contribution of this report is that discharge of CBM produced water has been examined from three different perspectives: regulatory, wastewater treatment, and long-term environmental fate-and-effect. Development of methane from coal seams in Alabama provided a unique opportunity to examine instream biological integrity and aquatic toxicity of produced waters that are surface discharged. The authors acknowledge that it is sometimes very difficult to determine whether the biological integrity of a receiving stream has been impaired by discharged wastewater but in many cases this determination is a requirement of environmental risk assessment. These studies indicated that with a monitoring approach surface discharge of moderately saline production waters is accomplished. The monitoring approach is termed the Cedar Cove Model and has four components: water quality characterization; aquatic toxicity testing; instream bioassessment; and continual water quality monitoring. Key features of this approach are highlighted below.

- Water quality characterization is the basis for monitoring because it provides chemical concentration data for permit compliance, toxicity evaluation, and assessment of instream biological integrity.
- Aquatic toxicity testing allows evaluation of the hazard of discharged effluents.

- Instream bioassessment ascertains the long-term basin-wide fate and effect of discharged effluents.
- Continual water quality monitoring is important for tracking instream salinity gradients of discharged waters.

A significant contribution of the Cedar Cove studies was to define a threshold level for chloride in produced water. A threshold value of 565mg/L chloride was determined, below which no significant effects on instream fauna were detected. Concentrations above this threshold consistently caused degradation of aquatic faunal communities in the receiving stream. Instream studies confirmed predictions made through laboratory toxicity tests. This is significant because the concept of regulating and controlling effluents using aquatic toxicity tests is predicated on the concept that laboratory tests can be used to estimate ecosystem effects.

Unlike conventional gas production, waters produced from coal seams are generally lower in concentration of salts, metals, and organics. Many factors affect the quality of coal seam production waters, but of primary significance are the depth and type of producing coal seams. In Alabama water from deeper coals is more mineralized than water from shallow coals that are more likely to have hydraulic connections with less mineralized shallow groundwater. In that region CBM produced waters are categorized as: fresh (under 1,000 mg/L TDS); slightly saline (1,000-3,000 mg/L TDS); moderately saline (3,000-10,000 mg/L TDS); or very saline (10,000-35,000 mg/L TDS). The aerial variation in salinity of production waters can be significant. For example, water samples from four wells in the Cedar Cove Field on the same date ranged in TDS from 2,100 to 7,900 mg/L. When water from these four wells and four additional wells was collected in a common settling lagoon, the mixed water had intermediate salinity regimes compared to individual well waters because of the dilution and mixing functions of lagoons.

Coal seam produced water has other significant chemical and physical characteristics besides salinity. Important variables include: total ionic concentration; pH; concentration of nitrate (NO_3 as N); concentration of metals (particularly iron, barium, strontium, lithium, arsenic, cadmium, chromium, lead, mercury, as well as aluminum, cobalt, copper, nickel, selenium, silver, vanadium, and zinc); turbidity; dissolved oxygen; and dissolved organic compounds.

Treatment technologies for disposal of CBM produced water include the following:

- Storage lagoons, both naturally aerated and mechanically aerated (these provide most of the produced water treatment in Alabama). Because storage is a key function of lagoons for the methane industry, treatment technologies were developed around this requirement. Storage is critical because during low streamflows in summer production water generally must be discharged at reduced rates compared to higher discharge rates possible in winter.
- Simple stabilization lagoons were used in the early stages of CBM development in Alabama. They are shallow enough to have sufficient oxygen produced photosynthetically and large enough to provide water storage.
- Aeration lagoons are used when shorter water retention times are desired.

- Electrodialysis and reverse osmosis, involving membrane technologies, are now economically feasible treatment alternatives for produced water that has high concentrations of dissolved solids. The membrane process can be divided into those that are pressure driven (reverse osmosis and ultrafiltration) and those that are electrically driven (electrodialysis). Inorganic constituents in produced water can be removed readily by reverse osmosis. Membrane processes in wastewater treatment can remove organic substances as well as inorganic substances.
- Evaporation (distillation) processes for treating saline water utilize the fact that only water and gasses dissolved in it are volatile, whereas the salts are not.
- The authors suggest that low cost treatment technologies such as stabilization lagoons have appeal not only in the United States but in other countries, such as China and Poland, where there are attempts to develop coalbed methane in the most affordable way possible.

Onsager, P.R.; Cox, D.O. 2000. Aquifer controls on coalbed methane development in the Powder River Basin, Wyoming. Paper presented at 2000 SPE Annu. Tech. Conf., Oct. 1-4, 2000, Dallas, TX. SPE Reprint 63090. 8 p.

Compared to other CBM producing basins, the Powder River Basin sub-bituminous coal has relatively low gas content but high permeability. Because of the shallow depth, CBM development is normally on 40- or 80-acre well spacing. Another significant difference between the Powder River Basin and other CBM basins is that Powder River coal seams are overlain and underlain by large, thick aquifers described as “infinite-acting in nature”. The degree of hydraulic connection between these aquifers and the coal is a critical factor in the economics of CBM production in the area. Some key conclusions were:

- The average cumulative production for the top 50 water producers through March 2000 was 1.23 million barrels water per well but only 187,000 Mcf gas for an overall cumulative gas/water ratio of 0.15 Mcf/barrel water.
- In contrast to the top water producers, the average cumulative production for the top 50 gas producers was 572,000 barrels water per well and 398,000 Mcf gas, for an overall gas/water ratio of 0.7 Mcf/barrel water. The higher gas/water ratio of the best gas producers is indicative of much lower leakage from the aquifers.
- When the aquifers are well connected to the coal, water influx is high, leading to a nearly steady state pressure environment that will deter efforts to dewater the coal for methane production.
- Optimum well spacing in the Powder River Basin depends on having sufficient wells per section to lift the water that leaks into the coal from the aquifers.
- CBM producibility in parts of the Powder River Basin is controlled by leakage from overlying and underlying aquifers. The degree of aquifer leakage is mainly a function of the confining layer permeability.
- The optimal well spacing partly depends on the degree of aquifer leakage in a given area. In each area, there must be sufficient wells to overcome the additional water influx due to aquifer leakage.
- In areas where aquifer leakage is high, even 40-acre well spacing may not provide enough dewatering to allow commercial quantities of methane to desorb. The need for high water production rates negatively impacts the economics of a CBM project

and results in lower gas recovery efficiencies. In some areas of this study, 80-acre well spacing was appropriate.

Ortiz, I.; Weller, T.F.; Anthony, R.V.; Frank, J.; Linz, D.; Nakles, D. 1993. Disposal of produced waters: underground injection option in the Black Warrior Basin. *In* 1993 International Coalbed Methane Symposium, May 17-21, 1993, Birmingham, AL. Univ. Alabama, Tuscaloosa, AL pp. 339-364.

Proper planning requires consideration of total coasts of CBM production. A key component of total cost is operating a brine disposal system and its required capital investment. Several issues must be addressed to understand the true cost of brine disposal. Generally, in the oil and gas industry, brine is disposed via underground injection where the cost of disposal is dictated by: depth of the receiving formation; formation characteristics (thickness, permeability, pore pressure, frac gradient, porosity, and injection area); and maximum allowable wellhead injection pressure. Anticipated fluid volumes to be injected into each well, well life, and number of required injection wells influence the total costs of managing an r injection project. This paper describes an underground injection cost model that optimizes costs based on hydraulic fracture design under specified reservoir conditions. The model can be used in all saltwater disposal applications, whether from CBM or conventional oil and gas operations.

Patton, C.C. 1999. Treatment of produced water from coal-bed methane production using carbon aerogel technology. U.S. Environmental Protection Agency, Nat. Cent. Environ. Res., Off. Res. & Devel. EPA Contract 68D60031. Phase 1. 2 p. Abstract.

The high cost of water disposal and lack of efficient technology for water treatment are barriers to expanded development of CBM reserves. Many of the areas where CBM is produced are arid and can benefit from creation of additional water supplies. If CBM water can be economically and efficiently treated to make it acceptable for surface discharge it becomes a resource instead of a waste. Benefits can be achieved through both agricultural uses and human consumption uses. Currently, treatment of produced water frequently requires use of reverse osmosis technology. The author describes a study proposal to demonstrate the effectiveness of capacitive deionization technology for treatment of CBM produced water. An attraction of this alternative is that it would use about 1/10 the energy required for reverse osmosis and would have a significantly smaller waste stream than reverse osmosis.

Peacock, K. 1997. Assessing the cumulative impacts of surface mining and coalbed methane development on shallow aquifers in the Powder River Basin, Wyoming. *In* J.E. Brandt, editor. Proc., 14th Annu. Mtg. Am. Soc. Surface Mining and Reclamation, Austin, Texas. pp. 648-666.

The author, a BLM hydrologist, describes a regional groundwater model, focusing on 790 mi^2 in the Powder River Basin near Wright, Wyoming, to simulate the impacts from three surface coal mines and CBM development proposed in a location structurally downdip from the coal mines. This modeling was in response to a finding by the Office of Surface Mining that there was a deficiency in Wyoming's coal-permitting process with regard to Cumulative Hydrologic Assessments for surface coal mining. Specific objectives of the modeling were to: model aquifer stresses to the Wyodak Coal Formation and the Wasatch Formation under two development scenarios (only historic and future surface mining, versus both surface coal mining and CBM development); provide a dynamic tool to assess likelihood of damage from current and future energy development; and provide initial quantification of recharge dynamics at the coal-clinker interface. Some of the key findings were as follows.

- Range fires and lightning strikes have periodically ignited exposed coal, forming surface clinker deposits. Clinker is highly permeable and can become saturated from infiltration of precipitation and snowmelt. Ponding of water may occur where clinker meets the less permeable coal and other sediments.
- Hydrologic and hydraulic variables used in the modeling included: hydrologic boundaries; lineaments and faults; hydraulic properties such as hydraulic head for the coal, clinker, and Wasatch Formation; storage coefficient; hydraulic conductivity; anisotropy; recharge to the top layer from precipitation and snowmelt; and water sources and sinks including aerial recharge and mine pits modeled as drains.
- Assessing anisotropy of the coal aquifer, quality checking of *in situ* aquifer tests, and database quality control were precursors to modeling.
- Data needs for regional modeling of this nature are extensive. Decisions must be made on data quality and adaptability of data to geographic information systems. This is costly but necessary as a scientific basis for modeling impacts of CBM development.
- Coalbed methane is regulated separately from surface mining. This separation is relevant because CBM development increases the extent of aquifer drawdown. It is therefore necessary to assess the relative proportion of drawdown attributable to each of coal mining and CBM development if liability for impacted water wells becomes an issue. Modeling such as described here addresses these concerns for all parties.

Pelley, J. 2000. Citizens outraged over methane mining damages. Environ. Sci. Tech. 34(13):294A.

In April 2000, the Wyoming Department of Environmental Quality placed 77 CBM well permits on hold after the Powder River Resource Council complained that the high sodium content of discharge water was harming the arid environment by eroding stream channels, polluting soils with sodium, and violating the Clean Water Act. In the same month the Montana Board of Oil and Gas placed a moratorium on new CBM permits when a lawsuit by the Northern Plains Resource Council charged that the state should not issue permits until an environmental impact statement is completed.

In this region, the average CBM well pumps over 6 million gallons water per year. An EPA environmental engineer contends that the sheer volume of discharge water has harmed the Powder River Basin, an arid area with highly erosive soils. In addition, the high sodium content makes CBM water unsuitable for irrigation and there are no federal standards for sodium. Water quality permits issued under the Clean Water Act are not typically used to control the quantity of discharged water, except where a maximum pollutant load has been established. Wyoming has asked the oil and gas industry to provide information about CBM produced water impacts on irrigated soils. Montana is also developing a new permitting system that will indirectly cap increased streamflow through dilution ratios that limit the volume of discharges into streams.

Petroleum Association of Wyoming. 2001. Letter Feb. 7, 2001 re: Wyodak Drainage Coal Bed Methane Environmental Assessment. Addressed to Mr. Paul Beels, Bureau of Land Management, Buffalo Field Office, WY. 6 p.

The Petroleum Association of Wyoming (PAW), representing most of the gas and oil producers in the state, raised several points relating to the Wyodak CBM environmental assessment:

- It was previously assumed that CBM water discharged into Wyoming stream channels would be reduced in volume by about 1% per mile as a result of evapotranspiration and infiltration into alluvium and other substrates. The PWA and others now think that the rate of reduction is greater than 1% per mile.
- The PWA believes that, although some CBM water may not be suitable for irrigation of crops, the quality of CBM water in Wyoming is generally suitable for livestock consumption. Suitability for irrigation is dependent upon interaction of discharged water with soil types, sodium adsorption ratios, salinity values, and crops grown. In many cases CBM water has been used for irrigation.
- The PAW thought that there needed to be quantification of the statement "There is potential for increased frequency and magnitude of localized flooding where channels or basin capacity is insufficient to handle the increased flows." They urged BLM to add information to the environmental assessment that would identify what to expect for channel capacities during certain storm events in relation to expected CBM discharge volumes.

Phelps, S.D.; Bauder, J.W. 2001. The role of plants in the bioremediation of coal bed methane product water. *In* Montana State University, Dept. of Land Resources and Environmental Sciences, Bozeman, MT. Water Quality and Irrigation Management, Position Pap. 11 p.

In the Powder River Basin water that is co-produced during CBM extraction is spread on the land or impounded in ephemeral drainage ravines. This water has the potential to elevate the saline-sodic conditions of soil, causing decreases in land productivity. The authors hypothesize that certain species of plants can uptake excess salts and remediate the saline-sodic conditions associated with CBM discharge water. The authors review studies from Europe, Egypt, and elsewhere in the United States that suggest halophytes can successfully achieve salt uptake by their root systems. Some observations by the authors include:

- Certain field crops, particularly barley, wheat, sorghum, cotton, and sugar beet, have been used extensively in phyto-remediation of saline-sodic sites at many places in the world. The authors list 17 plant species that are potentially useful as ion accumulators, ion extractors, or pore size enhancers.
- A saline soil is defined as a situation where electrical conductivity of a saturated extract is greater than 4 mmhos/cm. Salinity has the potential to adversely impact plant communities and forage capabilities for livestock and wildlife. Without a well-drained soil, salinity associated with CBM discharge water may accumulate in the upper soil layers and cause these undesirable impacts.

- Saline-sodic conditions created by CBM discharge water require mitigation if soils are to be returned to previous capabilities. Fortunately, there is considerable applicable soil science information developed before CBM water discharges became a concern.
- In combination with scientific irrigation strategies, interseeding, crop rotation, and post-discharge amendments such as addition of gypsum, predevelopment land capabilities can be achieved.

Powder River Coalbed Methane Information Council, Wyoming and Montana. 2001. Water Overview, and Environmental Issues. Various paging.

This Council is made up of production, gathering, and transportation companies active in the Powder River Basin. The Council's mission is to promote public understanding and safe operations in relation to CBM development. Following are some key points on the Council's web site (http://www.cbmwyo.org/):

- CBM wells typically go through three stages during their production cycle. In the initial depressuring stage water is produced with little or no gas. In a second stage volume of water continues to decrease while the volume of methane produced increases. Third is a stable production stage when the amount of methane is maximized and water production continues to decrease.
- In the Powder River Basin CBM water is discharged on the surface and runs into natural drainages or ponds, or is placed in reservoirs or stock tanks. Surface owner agreements generally deal with discharge water and its uses.
- Where CBM water does not meet Wyoming standards, the Department of Environmental Quality will not issue a discharge permit. Potential solutions in such cases include: lined impoundments; chemical treatment; or possible reinjection into aquifers.
- Quantity of discharged water has been a concern. Stream channel capacity studies are being completed to identify areas where increased flows may be an issue if they occur. In some areas operators are retaining water in reservoirs that not only mitigates downstream concerns but also allows beneficial use on the site and recharge of shallow aquifers.
- Ranchers and landowners have been using CBM water as a source for domestic and stock watering for decades. Although water quality varies across the basin, in most cases water samples meet Wyoming's water quality standards.
- One water quality concern is the relationship of sodium to magnesium and calcium (SAR). Water with high SAR, when mixed with natural salts present in the soil, increases total soil salinity, causing plants to die and erosion to increase.
- CBM wells produce at relatively low pressure and require the assistance of compression to reach pipeline pressure. Technologies to reduce impacts on air quality include: lean burning engines, computer assisted controllers for air /fuel ratios; and exhaust catalysts.
- Other concerns have been raised about dust. Unlike traditional oil and gas operations, CBM wells take a few days to drill with little traffic in and out of the drill site in that limited time frame. Minimal road building is done during CBM development.

- Impacts on wildlife are primarily from surface disturbance. Facilities are often fenced to protect both domestic and wild animals. The nature of CBM operations is such that little monitoring is needed, which reduces traffic disturbances to wildlife.

Powder River Basin Resource Council. 2001. Coalbed methane development in Wyoming's Powder River Basin is transforming the landscape – PRBRC and landowners respond to prevent damage. PRBRC, Sheridan, WY. 5 p.

CBM extraction in the Powder River Basin is expected to have significant detrimental consequences because 50,000 to 120,000 wells are projected over the next 15-30 years. Water must be pumped from the targeted coal seams at rates up to 100 gal/minute/well, for as long as the first two years of a well's operation. Discharge of this water is already causing extensive erosion and in some cases irreversible soil damage from the high salt and sodium content of discharge water. Other concerns expressed by the Council include:

- Over 400 miles of power lines were constructed in the year preceding this report and over 400 miles are projected each year for the next 5-6 years to provide power to CBM wells and compressor stations. Noisy compressor stations powered by jet engines have disturbed the solitude of rural living and hundreds of trucks create dust.
- Eighty percent of Wyoming's residents depend on groundwater for drinking water, and this resource is being pumped to the surface resulting in loss of water for current and future users.
- Some of the tested CBM water contained higher levels of arsenic, iron, barium, and manganese than previously expected. The Council indicates that CBM discharge water is generally unsuitable for lawn watering and irrigation.

Raymond, R.N. 1991. Regulatory aspects of permitting and operating a Class II salt water disposal (SWD) well in the coalbed methane production areas of Alabama. *In* Univ. Alabama, Coll. Cont. Studies & Coll. Engineering. Proc. 1991 Coalbed Methane Symp., May 13-16, 1991. Univ. Alabama, Tuscaloosa, AL. pp. 69-73.

Class II injection wells, or saltwater disposal (SWD) wells, are used to dispose of brine brought to the surface in connection with CBM operations. Alabama's Class II Underground Injection Control Program uses Rule 400-1-5-04 that provides guidance on protection of the state's underground sources of drinking water. Permitting a SWD well involves two steps, both requiring submittal of certain forms and presentation of geological, engineering, and water chemistry data. Step 1 involves approval of an application to drill or to convert an existing well following a 15-day comment period. Step 2 requires the approval of an application to inject fluids.

Reed, M.; Johnsen, S., editors. 1996. Produced water 2: environmental issues and mitigation technologies. Plenum Press, New York. Environ. Sci. Res. Ser. Vol. 52. 536 p.

This text results from the 1995 International Produced Water Seminar, Trondheim, Norway. None of the articles deal with CBM produced water but some of this text's principles for handling produced water from oilfield facilities may be applicable to CBM operations.

Regele, S.; Stark, J. 2000. Coal bed methane gas development in Montana, some biological issues. Montana Dept. Environ. Qual., Industrial & Energy Minerals Bur., Billings, MT. Presented Sept. 1, 2001 at Interactive Forum on Surface Mining Reclamation Approaches to Bond Release: Cumulative Hydrologic Impacts Assessment (CHIA) and Hydrology Topics for the Arid and Semi-Arid West. Coal-Bed Methane Workshop.

In relation to produced water from CBM operations, the authors listed three categories of concern:

- Waters generated from CBM may significantly drawdown local and regional aquifers and reduce important ground and surface water supplies. Possible effects include: springs, streams, domestic and stock water wells, and irrigated acreages could be diminished or could dry up; crop production may be diminished; carrying capacities and distribution patterns for livestock and wildlife could be adversely affected; diminished flows from aquifers could reduce the ability to develop aquifers for domestic or agricultural uses; reduced flows can negatively impact aquatic and terrestrial biota, local or regional ecosystems, and economies dependent on such biota or ecosystems.
- CBM discharges may cause substantial flows in normally dry watercourses such as ephemeral streams, coulees, and gullies. Possible effects include: vegetation in stream channels may be destroyed when water flows in drainages that otherwise have flow only part of the year; increased flow can result in greater channel erosion, loss of soil, increased sediment loads, and degraded water quality; such changes can adversely affect algae, aquatic invertebrates, fish, amphibians, and other biological aspects of streams; increased deposition of sediment can adversely affect receiving streams and reservoirs.
- Some of the CBM discharge waters could contain pollutants such as arsenic, ammonia, boron, iron, manganese, radium, and fluoride. Increases in salinity, sodium concentration, and other soluble pollutants are likely to occur in streams receiving water discharged from CBM development. Possible effects include: CBM-produced water may have substantial adverse chemical impacts on irrigated lands and crops, livestock, wildlife and fish populations, and aquatic biota; crops can tolerate salinity up to certain levels but beyond threshold levels crop yields decrease as soil salinity increases; soil salinity levels may exceed salinity levels in irrigation water because of salt accumulation associated with repeated irrigation; CBM-induced changes in irrigation water chemistry may affect soil fertility, plant available moisture, crop yields, and cropping flexibility.

The authors described two additional environmental concerns in relation to CBM development.

- Lower water tables near coalmines could adversely affect current coalmine permits, hinder reclamation potential, and interfere with the release of reclamation bonds. The main concern is that coalmine reclamation plans are generally based on an assumption of unaltered hydrologic balances to sustain post-mining land uses involving livestock grazing or fish and wildlife habitat, but these assumptions may not apply if CBM projects significantly alter local and regional hydrologic systems.

- Creation of a widespread network of new trails and roads, increased use and impact on existing trails and roads, and significant surface disturbances resulting from compressor stations, holding ponds, and pipeline construction can significantly affect natural resources and land uses. Possible effects include: surface disturbances can lead to significant erosion and noxious weed concentrations if they are not properly managed and maintained; there may be reduction of acreage and forage available for use by livestock and wildlife; human activities associated with CBM production can adversely affect feeding, nesting, and breeding grounds for various wildlife species; CBM holding ponds may provide short-term benefit as water sources for livestock and wetland habitat for wildlife, but the typical life expectancy of a CBM development site is about 20 years after which removal of the produced water supply could influence waterfowl and wildlife species that had become dependent on CBM holding ponds; such holding ponds may become “salt lakes” and saline seeps can develop down slope from such water bodies, resulting in possible adverse effects on vegetation, soils, and water quality of any receiving streams.

Rice, C.A.; Nuccio, V. 2000. Water produced with coal-bed methane. U.S. Geological Survey Fact Sheet FS-156-00. 2 p.

In some areas coal beds function as regional or local aquifers. The water in coal beds contributes to pressure that keeps methane adsorbed to the surface of coal. This water must be removed to allow desorption of methane from the coal. Over time, the volumes of pumped water decrease and production of methane increases as coalbeds near the well bore are dewatered. This USGS Fact Sheet indicates that:

- The amount of water produced, as well as the ratio of water to gas, varies widely among CBM basins. Causes of variation include duration of CBM production in the basin, original depositional environment, depth of the coal bed, and type of coal.
- Generally, dissolved ions in CBM produced water contain mainly sodium, bicarbonate, and chloride. The bicarbonate component potentially limits the amount of calcium and magnesium through precipitation of carbonate minerals. CBM waters are relatively low in sulfate because the chemical conditions in coalbeds favour conversion of SO_4 to sulfide. Total dissolved solids (TDS) of CBM waters range from fresh (200 mg/L or ppm) to saline (170,000 mg/L) and varies among and within basins. For comparison, the recommended TDS limit for potable water is 500 mg/L, and for beneficial use such as livestock ponds or irrigation the limit is 1000-2000 mg/L. Average seawater has a TDS of about 35,000 mg/L.
- The TDS of produced water is dependent on depth of the coalbeds, composition of rocks surrounding the coalbeds, amount of time that the rock and water react, and origin of water entering the coalbeds.
- Trace element concentrations in CBM water are commonly low (under 1 mg/L), as are volatile organic compounds. In general, most CBM water has better quality than waters produced from conventional oil and gas wells.
- Water co-produced with methane is not reinjected into the producing formation to enhance recovery, as is the practice in many oil fields. Instead, water must be disposed or used for beneficial purposes. The choice of disposal alternative depends on the composition of the water.

- The important composition information includes: TDS (often equated to the amount of ‘salt’ in the water); pH; concentration of dissolved metals and radium; and the type and amount of dissolved organic constituents.
- Disposal of CBM water is regulated by federal and state agencies and must meet criteria for each type of disposal. For example, subsurface injection requires compatibility studies of the proposed injection formation and the water that is to be injected, whereas discharge to surface streams must meet daily effluent limits on constituents such as chlorides along with other criteria.
- For any CBM field, the cost of handling produced water varies from a few cents to over $1/barrel. In some areas the volumes of water produced and the cost of handling it may prohibit development of the CBM resource.
- CBM water studies typically include the use of sampling wells throughout a field to record volumes of water produced and to analyze major, minor, and trace constituents including: arsenic; selenium; copper; cadmium; lead; molybdenum; chromium; mercury; and zinc. The major anions (chloride, sulfate, and bicarbonate) are measured, as well as selected other constituents such as ammonia and total organic carbon. Isotopic analyses for deuterium, oxygen, and carbon can help determine the origin of produced water as well as the compositional evolution of the water.

Rice, D.D.; Wanty, R.B. Byrer, C.W.; Kruger, D.W. 1995. Coalbed methane – from hazard to environmental concern and untapped energy resource. *In* L.M.H. Carter, editor. Energy and the Environment – Application of Geosciences to Decision-Making, 10th V.E. McKelvey Forum on Mineral and Energy Resources, 1995. USGS Circ. 1108. pp. 72-74.

Coalbed gases are variable in their composition. Although methane is generally dominant, significant amounts of heavier hydrocarbon gases, carbon dioxide, and nitrogen can also be present. In addition, hydrogen-rich coalbeds can generate and sometimes produce liquid hydrocarbons that are viscous and can cause problems for production. Because coal has large internal surface areas, it can store large amounts of gas, much more than the same rock volume of a conventional gas reservoir. Permeability is essentially nonexistent in the matrix of coal, but is developed in fractures, commonly referred to as cleats. The cleats are generally filled with water. The sources of water are: original water from the time that peat was deposited; atmospheric sources; and adjacent aquifers. In some places, cleats may be filled with gas above the water table.

CBM wells have a distinctive production history characterized by: an early stage when large amounts of water are produced from the cleats to reduce reservoir pressure and to initiate release of methane from the internal surface areas; a stable stage when quantities of gas increase as quantities of produced water decrease; and a late stage when the amount of gas declines and water production remains low. The volume of water produced from an individual CBM well is generally much higher than that produced from individual oil or gas wells. The quantity and quality of water vary considerably in CBM basins and reflect the water’s residence time, rock-water interactions in the subsurface, and groundwater flow patterns. Water quality and quantity are generally lower in the central, deeper parts of basins compared to the shallower parts that are near recharge areas of relatively fresh atmospheric water.

Environmentally acceptable options of water disposal include surface discharge or underground injection. Another alternative is evaporation and collection of solid residues. Because CBM waters are commonly rich in sodium, carbonate, and chloride, the possibility exists that evaporation products may be trona (sodium sesquicarbonate) and halite (sodium chloride), both salable commodities.

Robinson, K.; Bauder, J.W. 2001. A novices introduction to CBM. *In* Montana State University, Dept. of Land Resources and Environmental Sciences, Bozeman, MT. Water Quality and Irrigation Management, Position Pap. 2 p.

Development of the CBM industry is well underway in Wyoming whereas development in Montana is delayed while an environmental impact statement is being written and litigation addressed. CBM extraction in Montana is not without controversy. The quantity, quality, and dispersal of produced water us a source of much debate. Each well is expected to produce between 5 and 20 gallons of water per minute. When considered as an irrigation supply or when spread on the land, water of CBM quality could alter soil physical and chemical properties and limit productivity of some rangeland species. On the positive side, appropriate management practices and bioremediation can allow CBM product water to be a valuable supplement to existing water supplies. Research at Montana State University – Bozeman to find the best ways to manage CBM water is focusing on: standards and criteria which discharge water must meet before release into waterways or onto land; acceptable and sustainable guidelines of mixing ratios of CBM water with irrigation water; and use of artificial wetlands and specific plant communities for bioremediation of discharge water.

Rocky Mountain Operating Company, Inc. 1993. Investment opportunities with Rocky Mountain Operating Company, Inc. Western Interior Coal Region (Arkoma, Cherokee, and Forest City Basins). Quart. Rev. Methane From Coal Seams Tech. 11(1):43-48.

The CBM potential of the Western Interior Coal Region, represented by the Arkoma, Cherokee and Forest City Basins, is not as well documented as the methane resource in coalfields of Alabama and the Rocky Mountain states.

- Shallow, water-poor coal reservoirs are a distinctive feature of some parts of the Western Interior Coal Region. For example, the Arkoma Basin in Oklahoma and Kansas has low water production, despite substantial coalbed permeability, indicating that the coal seams do not act as aquifers.
- Land surface disturbances from CBM development in this region have been reduced by reuse of older oil and gas wells to tap into coal seams, although many new CBM well have also been drilled.
- In the Cherokee Basin produced water has been injected into Arbuckle Group carbonates using inexpensive ($20,000) disposal wells. Each injection well can handle produced water from 10-20 CBM wells, so water disposal is not a major operational expense.

- In the Cherokee Basin thick water-bearing sands lie above and below the coal seams in some areas, and operators avoid large-volume fracture treatments that could link the coal seams to these horizons and lead to excessive water production.
- Existing pipeline access is an economic advantage for CBM development in the Western Interior Coal Region.

Rogers, R.E. 1994. Coalbed methane: principles and practice, PTR Prentice Hall, Englewood Cliffs, NJ. 345 p.

Of all the information sources annotated, this text is the single most informative reference. It is the only single-author CBM textbook found in this literature review. It is a comprehensive synthesis of the CBM resource, geological influences on coal, principles of adsorption in coal seams, coal reservoir analyses, water production and disposal, completions and production in CBM operations, hydraulic fracturing of coal seams, and economics of CBM recovery. In relation to CBM produced water, the text outlines water production rates, chemical content of CBM waters, environmental regulations to handle such water, and water disposal techniques. The text does not address other environmental or land-use aspects of CBM development. Some annotated excerpts of the text are provided below.

- Prior to this book, hundreds of individual articles appeared in the technical literature describing most aspects of the CBM process, but principles and their application had not previously been organized into a single reference. This text focuses mainly on the engineering aspects of CBM production.
- Drilling and production techniques of the oil and gas industry were used initially to extract methane from coal. However, significant differences in coalbed reservoir properties, gas storage mechanisms, gas transport phenomena, resource decline, and water disposal have required CBM innovations to the conventional oil and gas procedures.
- Initial costs can be high for disposal of CBM water early in the life of a well but these costs decline rapidly. For example, water production rate in the Black Warrior Basin typically drops by 70-90% in the first two months. Exceptions to the pattern of CBM water production occur when wells are located near active coalmines that have already been dewatered by mining. Another exception is in the under-pressured coalbeds in some western Cretaceous coals.
- Water composition is a possible indicator of coalbed permeability. For example, in San Juan Basin, a high concentration of bicarbonate ions in CBM waters is an indicator of favorable permeability, while high concentrations of chloride ions imply stagnant waters that have insignificant meteoric recharge.
- Interference of one CBM well with an adjacent well has a positive effect on methane production if dewatering of the seams is facilitated by the interference. Permeability, hydraulic fracturing length, and well spacing are important to understand for field development because of their influence on the interference effect. This means that CBM projects are developed on a field-wide scale instead of as isolated wells. A five-spot pilot project is a minimum requirement to evaluate ultimate field performance.
- There is a possibility of lower gas production from larger spacings between CBM wells because of the difficulty in removing water from the coal seam. Dewatering

depends on permeability of the coal (cleats and induced fractures) and well spacing. In the San Juan Basin, an 80-acre spacing provided a peak production rate much sooner than larger spacings because of the positive influence on dewatering.

- Water production and disposal assume a greater importance in CBM projects than in conventional oil and gas operations. In marginally economic CBM projects, water disposal costs and required environmental accounting are critical factors in the investment decision; water disposal costs can economically make or break a marginal CBM project.
- High initial water flow rates normally decline as the methane production rate increases, which is counter to the conventional oil and gas process. Lack of understanding of the unusual pattern of water flow and its relation to methane desorption probably delayed recognition that methane could be produced profitably. Many early CBM operators lacked the persistence to produce and dispose of enough water to create commercial amounts of methane.
- Another dissimilarity with conventional oil and gas wells is that well-to-well interference in CBM methane fields is beneficial because of the mutual assistance in water removal. The interference characteristics impose another economic demand on the CBM process – a commitment to develop the entire field that requires a large capital investment. Development of a lone CBM well is impractical.
- Water associated with a CBM project involves three forms. First, adherent moisture (bulk moisture) refers to free water contained in the cleat system that has a normal vapor pressure. This adherent moisture is the water that must be disposed in CBM work. Second, inherent moisture (adsorbed moisture) is the water in the micropore system that decreases the adsorptive capacity of the coal for methane. Inherent moisture is not relevant in water disposal problems but it is detrimental by limiting gas content. Third, chemically bound water may have been incorporated in the molecular structure of coal at the start of peat formation. Temperatures higher than any encountered in the CBM process are required to release this form of water.
- There are wide variations in water production rates from coals in any one basin. Ease of dewatering any one CBM well depends on the coal's permeability, interference with other wells or coalmines, and links to aquifers. Records from 420 CBM wells in the Black Warrior Basin had initial production rates of 17 to 1,175 barrels water/day, averaging 103 barrels water/day. Initial water production rates in the San Juan Basin averaged 14 to 1,000 barrels water/day with an average rate of 70 barrels water/day. Water production profiles of CBM wells show rates that normally peak within one year and then decline throughout the remaining life of the well unless the coal has high permeability and contact with an aquifer or meteoric waters.
- Ranges of chemical composition parameters are shown in a following table for CBM waters from the San Juan and Black Warrior Basins.

Parameters	Warrior Basin, Alabama Range of values, mg/L	San Juan Basin, Colorado Range of values, mg/L
pH	6.5-9.2	7.4-8.8
Anions		
Bicarbonate	76-12,000	7.8-1,450
Chloride	19-15,000	1-720
Fluoride	nd-20	0.1-3.6
Sulfate	nd-650	nd-2,700
Metals		
Barium	0.2-37	na
Cadmium	nd-0.026	na
Calcium	nd-620	3-460
Iron	0.005-246	nd-5
Lithium	0.18-33	na
Magnesium	0.3-420	0-150
Manganese	0.005-3.8	na
Potassium	0.3-24	1.1-8.5
Silicon	0.2-14	6.8-15
Sodium	0-6,800	26-1,290
Strontium	0-56	na
Zinc	0-0.36	na
TDS	550-26,700	263-4,050
BOD	100-300	na
Hydrocarbon	1-62	na

- The main chemical contents and conditions that are regulated in CBM discharge waters are: dissolved oxygen, biochemical oxygen demand (BOD), iron, manganese, and total dissolved solids (TDS). The first four of these regulated conditions are dependent on adequate oxygen being added to the produced water before it can be disposed in surface streams. Dissolved oxygen must be added to produced waters as coal seam waters are devoid of oxygen. Upon aerating the waters at the surface, iron and manganese are oxidized and precipitate as solids. BOD results from the bacteria that degrade organic compounds in water. The greatest amount of organic matter that must be biodegraded in CBM waters comes from fracturing fluids. Hydroxypropyl guar and other water-soluble polymers used in fracturing are the main culprits. To correct the heavy surge of BOD upon startup of a field some operators have added hydrogen peroxide to meet the oxygen demand.
- Removal of manganese and iron is more straightforward than TDS removal. The oxidized manganese and iron forms precipitates in the holding ponds. To assist gravity settling, the following conditions are imposed in treatment ponds: quiescent settling waters; greater than 24-hr detention time; ponds of at least 10-ft depth to allow accumulation of precipitates for several years between clean-outs; and baffled

exits of water from the ponds. Total dissolved solids are the most troublesome chemical content of produced waters and the most damaging to plant life. Sodium chloride is the main constituent of TDS.
- The author reviews in detail the four techniques available for disposal of CBM produced waters: well injection; discharge into surface streams; land application; and membrane processes. Those details are not annotated here as they are addressed in many of the annotated references by other authors.

Rudolph, J.; Miller, J. 2001. Downhole produced water disposal improves gas rate. Gas Technology Institute, Chicago, IL. Gas Tips Oct. 2001. 2 p.
The Gas Technology Institute (GTI, formerly the Gas Research Institute) in partnership with Down Hole Injection, Inc. is investigating ways to improve production economics of gas wells through water management strategies such as downhole water separation and disposal. The note focuses on water-producing gas wells, but also refers to handling CBM produced water. GTI's Produced Water Management Group noted that although U.S. costs of handling produced water are often recorded at about $1/barrel, the fully burdened cost of water disposal, including capital and operating expenses, is estimated between $1.30 and $2.00/barrel, depending on volume and site-specific conditions. One difficulty in estimating water disposal costs is that many companies do not recognize or account for the full cost of water management. Large companies are often organized in ways that compartmentalize operating functions and budgets. A result is that accounting for water-related costs is often spread over several corporate departments. Consequently, the economic cost of handling produced water is under estimated. Smaller operators may not have those problem but they tend to lack the resources needed for effective water management strategies.

Sadler, L.Y., III; George, O. 1995. Concentration of saline produced water from coalbed methane gas wells in a multiple-effect evaporator using waste heat from the gas compressor and compressor drive engine. Desalination 101:169-176.
Unlike conventional natural gas, which is associated with petroleum and usually reaches the wellhead at high pressure, CBM gas arrives at the wellhead at low pressure, usually around 101 kPa(1atm) and must be compressed near the well site for injection into gas transmission pipelines. The use of heat of compression from the gas compressor and waste heat from the diesel engine driving the compressor was assessed as a means of concentrating saline produced water to facilitate its disposal. The water concentration process was simulated for typical conditions in the CBM field of the Black Warrior Basin, but has application to other CBM fields. The study showed that the evaporator system could handle a produced water/gas ratio of 1.43 kg/m^3 (89 lb water/Mcf gas). It was demonstrated that this process could be considered for concentrating saline produced water in circumstances where the gas must be compressed near the wellhead before it is transported by pipeline to market.

Sauer, T.C.; Helder, J.C.; Brown, J.S.; Ward, T.J. 1997. Toxicity identification evaluations of produced-water effluents. Environ. Toxicol. Chem. 16(10):2020-2028.

Produced water is one effluent that is permitted under the NPDES for discharge into offshore waters even though it can exhibit both acute and chronic toxicity in laboratory testing. In the past, identification of produced toxicity typically involved direct chemical analysis of the entire produced water sample with inferences of toxicity made directly from the chemical composition of the effluent. A more recent approach to determine the toxic component of effluent has involved a toxicity-based concept called toxicity identification evaluation (TIE). TIEs were performed on 14 produced water samples of various salinities from inland and offshore oil and gas production facilities in Wyoming, Texas, California, and Louisiana. The samples did not include CBM produced water but the general conclusions may be applicable to toxicity testing of CBM waters. A key conclusion was that components contributing to toxicity differ for different sources of produced water, with no specific fraction being consistently toxic. No more than two fraction types were identified as potential toxicants in any one sample. Potential toxicants identified during this study, besides salinity, included: acidic and basic organic compound fractions; particulates removed by filtration at pH 11; ammonia; hydrocarbons; hydrogen sulfide; and volatile compounds.

Schneider, T.J. 2001. Coal bed methane development done right. Northern Plains Resource Council, Billings, MT. 4 p.

The author, a consulting petroleum engineer, used a mid-range projection of 26,500 CBM wells in the Montana portion of the Powder River Basin to estimate the total volume of water produced would be nearly 6 billion oilfield barrels (42 gals/barrel). This translates to a pool of salty water covering 1200 mi^2 one foot deep. He emphasizes that this water is not an answer to agricultural drought because most CBM discharge water is toxic to plants. The high concentration of dissolved salts not only kills plants but also destroys soil structure in the long term. It can be used to water stock but there are not enough livestock in the entire state to use the amount of water that will be produced. Discharging CBM water into rivers, creeks, or draws is the cheapest and easiest disposal method but the author is concerned about the impacts of this practice on farmers, ranchers, wildlife, vegetation, and aquatic ecosystems. On behalf of the Northern Plains Resource Council the author investigated the viability of reinjecting CBM water into the same coalbeds from which it was produced. He concluded that reinjection of CBM water is not only viable, but that it could mitigate most of the difficult surface water problems including degraded water quality, ecosystem changes, impact on irrigation and crop yields, water rights, aquifer subsidence, and aquifer depletion. Reinjection of water into the formation from which it has been pumped has been a recognized method for disposal of produced water in the petroleum industry. The author believes that reinjection into coal seams is the most direct and prudent approach to deal with both surface and subsurface aquifer impacts of producing unprecedented amounts of poor quality water.

Schneider, T.J. 2001. Coal bed methane produced water reinjection. Prepared for Northern Plains Resource Council, Billings, MT. 9 p. + attachments.

The author noted that BLM's reasonably foreseeable development forecast could involve up to 24,000 producing CBM wells in Montana. The cumulative produced water forecast could be nearly 6.0 billion oilfield barrels (42 gal/barrel), which would cover 135 townships 7.5 cm deep with saline produced water. The most direct approach to dealing with both surface and subsurface risks of these large quantities of produced water is to require reinjection of unaltered produced water into the coal seams of origin. Reinjection has been a recognized method for produced water disposal in the petroleum industry for decades. Reinjection eliminates a wide range of adverse surface water impacts, including damage to aquatic and wildlife ecosystems, threatened and endangered species, disruption of water quality in surface irrigation water and reservoirs, disruption of recreation values of rivers and streams, and contamination of soil and crops.

The author compared two alternatives: reinjection of unaltered CBM produced water back into the coal seam; and injection into other (non-CBM) subsurface formations. For either method of reinjection, it is important to recognize that CBM water production rates are at maximum levels at the outset of production, and it is therefore essential that a plan for reinjection into the coal seams or injection into other acceptable subsurface formations be established prior to production. Some pros and cons of these two alternatives are outlined below.

Reinjection into coal seams eliminates the full range of surface water discharge issues, including damage to ecosystems, surface waters, irrigation systems, and crops. It also preserves coalbed aquifer pressure that feeds surface springs and water wells on which livestock and human water consumption may be dependent. Reinjection also mitigates risk of coalbed fires. Some of the disadvantages of reinjection into coal seams include: problems at the outset of production since methane production typically requires a pressure drop via water production to increase rate of methane production; increased operating costs associated with reinjection; and landowners who rely on aquifers of coalbed origin are concerned that reinjection into the coalbed aquifer might damage the aquifer. The latter concern is addressed if only unaltered CBM water is recycled, using a closed loop from production to battery to reinjection wells.

Injection into non-CBM formations is attractive in some cases where it may be relatively inexpensive to convert marginal gas wells to reinjection wells. It is therefore important that early attention be given to identification of marginal gas wells that could be shut-in and then used for reinjection of CBM produced water. As with reinjection into coal seams, injection into other strata eliminates a variety of undesirable impacts associated with surface discharge of produced water. An advantage of injection to deeper strata is that it allows early draw down of pressure in the CBM formation to establish early methane production. This approach also allows later reinjection of produced water into the coal seam after gas production is well established. Some of the disadvantages include: once CBM produced water is injected into other deeper strata it is lost to the coalbed aquifer; in some cases there may be better quality water in the receiving formations and a concern for contaminating that water with poorer quality CBM produced water;

determining which deep formations are acceptable for CBM produced water disposal can require costly drilling and testing to establish injection rates; there is also some concern that produced water could create chemical reactions that plug or otherwise disrupt water movement in the receiving formation.

Shepard, T.E.; O'Neil, P.E.; Harris, S.C.; McGregor, S.W. 1993. Effects of coalbed methane development on the water quality and fish and benthic invertebrate communities of the Big Sandy Creek drainage system, Alabama. Geol. Surv. Alabama, Tuscaloosa, AL. Circ. 171. 89 p.

In 1989 the Geological Survey of Alabama initiated a study to characterize hydrologic conditions and biological communities prior to discharge of CBM waters and to document changes after discharge began. Natural surface waters were characterized by local concentrations of dissolved solids, neutral or slightly acidic pH, low alkalinity, and very low concentrations of metals. After produced water discharge began in 1990, concentrations of TDS increased significantly over pre-discharge levels. However, no decreases in diversity and abundance of fish or benthic invertebrates were detected at two stations downstream of discharge points. Some other points noted by the authors include:

- Although CBM produced waters are typically less saline than brine associated with conventional gas reserves, the CBM waters often contain much higher levels of dissolved minerals than surface waters, particularly chlorides, bicarbonate, iron, and some heavy metals.
- Benthic invertebrates offer several advantages as indicators of environmental disturbances in aquatic ecosystems. Their sessile mode of life and limited mobility means that most invertebrates spend much of their life in a small area, subject to any changes in the immediate environment. Physical or chemical changes in the stream environment are often reflected in changes in the invertebrate community.

Shuey, C. 1990. Policy and regulatory implications of coal-bed methane development in the San Juan Basin, New Mexico and Colorado. *In* Proc. 1st Intern. Symp. on Oil and Gas Exploration and Production Waste Management Practices, New Orleans, LA. pp. 757-769.

An upsurge in CBM development in the San Juan basin coincided with discovery of extensive methane contamination of an alluvial aquifer in the Animas River valley. Studies by state and federal agencies indicated that CBM production was at least partially responsible for presence of thermogenic gas in private domestic water wells, in alfalfa field seeps, at the surface casings and Bradenheads of gas-producing wells, and in cathodic protection holes along a 25-mile stretch of the river valley. This paper summarizes the scientific data that implicate CBM production in contamination of freshwater in the area. The mechanism by which CBM migrates upward nearly 3,000 feet to groundwater is described.

The author, at the time of this article Director of the Community Water Quality Program, Southwest Research and Information Center, Albuquerque, indicated that new policies and regulatory initiatives were needed to address this problem. He suggested: multi-jurisdictional planning and coordination; cumulative environmental studies; pre-lease environmental audits; cementing of existing gas wells; a moratorium on new leasing;

corrective action to remediate contaminated groundwater; a compensation fund for property owners impacted by CBM development; ongoing private water well testing; local land-use controls; and produced water minimization. The latter would require producers to minimize or reuse CBM produced water and should be incorporated into pre-lease audits or in applications to drill. The author suggested that agencies should be required to demonstrate prior to gas well completion that adequate water disposal capacity is available. Permitting of produced water haulers was also suggested to prevent illegal dumping of water when disposal space is unavailable. Some of the other topics addressed include:

- The scientific evidence that linked CBM development to contamination of fresh groundwater included: analytical data from 200 different domestic water wells; chemical and carbon isotopic composition data from 48 gas samples gathered from water wells, gas seeps in fields, surface casings of gas-producing wells, and cathodic protection holes adjacent to producing wells; and previous studies on genesis and geological origin of methane.
- Interviews with 15 different long-time residents recorded anecdotal accounts of methane in the alluvial river valley. Information from those interviews supplemented the scientific data. Observations of residents included: recent occurrences of gas bubbles in fields, seeps or wells; observation that a water well caught fire after a match was tossed into the bore hole; and observation that flames roared from a water well after an individual discharged a firearm into the borehole in hopes of opening the perforations at the bottom of the well.
- Based on their understanding of the gas migration problem and the regional geology, scientists concluded that natural fractures or other tectonic avenues did not contribute to release of methane prior to depressurization of coalbeds when they were developed for CBM production.
- The mechanism for gas migration was summarized as follows. Gas is freed from its host rock after formation pressures are lowered by CBM wells. The gas migrates from the coalbed into overlying strata via un-cemented portions of producing conventional gas wells that penetrate the Fruitland Coal Formation. Once inside the alluvial aquifer, the migrating methane can invade cathodic protection holes or domestic water wells. This gas migration theory was developed by geologists of the New Mexico Oil Conservation Division, based on previous water quality studies, pressure testing on gas wells, isotopic analyses of the migrating methane, and their own observations and insights. They discovered that many deeper gas wells were not cemented through the surficial alluvial aquifer nor were they cemented opposite their passage through the Fruitland Coal seams. The gas chemical and isotopic composition data subsequently reported by the U.S. Geological Survey confirmed that Fruitland coalbed methane was present at the surface casings and Bradenheads of nine different deep conventional gas wells.
- They author noted that the large volumes of CBM produced water vary greatly in dissolved solids content, are rich in bicarbonate and sodium, and exhibit concentrations of barium, gross alpha radioactivity, and total radium that exceed drinking water standards. At the time of this article, produced water from the San Juan coalbeds was stretching the available disposal capacity and forcing some operators to shut-in their Fruitland CBM wells.

Simmons, B.F. 1991. Treatment and disposal of waste waters produced with coalbed methane. *In* 1991 Coalbed Methane Symp., May 13-17, 1991, Tuscaloosa, AL. Univ. Alabama, Coll. Cont. Studies & Coll. Engineering. Tuscaloosa, AL. pp. 459-468.

RMI Environmental Services, Golden, Colorado, developed a treatment process for CBM produced water that is both economically and technically feasible. The treatment can be divided into three categories: pretreatment, which includes flotation/aeration, solids filtration, and chemical addition; TDS reduction using reverse osmosis; and disposal of concentrates using a combination of evaporation and crystallization. By this process, produced water disposal has several advantages: elimination of risks associated with drilling and operating injection wells; provision of flexibility to relocate the treatment equipment at different locations as water production decreases or ceases at successive CBM wells; creation of clean water for use by local consumers and to replenish runoff; and recycling of dissolved solids.

Society of Petroleum Engineers. 1992. Coalbed methane. Soc. Petrol. Eng., Richardson, TX. SPE Reprint Ser. No. 35. 237 p.

The Society of Petroleum Engineers devoted one volume of their SPE Reprint Series to 20 selected papers that the Society thought would best summarize the technology used, as of 1992, to develop CBM reservoirs. This collection of articles does not provide information on water handling, environmental, or land-use aspects of CBM development. However, several papers in this volume explain the differences between CBM reservoirs and conventional sandstone or carbonate reservoirs, and describe some unique petroleum engineering aspects involved with CBM development. Unique aspects such as gas desorption and diffusion characteristics, high fracture treatment pressures, the need to dewater the reservoir before methane production begins, and the weak, unstable nature of coal and its effect on well completions are some of the characteristics that make CBM reservoirs different from conventional natural gas reservoirs.

An important feature of this volume is its comprehensive coverage of CBM literature. More than 200 papers were reviewed to assemble this volume and all of these references are listed at the end of the volume. Besides the 20 key papers, this volume includes an annotated bibliography of 36 additional papers. The annotated bibliography provide substantial information on hydraulic fracturing to enhance production of methane from coal seams, as well as other engineering aspects of CBM development. The volume does not include papers on coal geology, coal petrology, or basic coal properties. The editors of this volume emphasize that a problem in completing the book was that the subject was a moving target because coalbed methane was a topic attracting a lot of attention.

Southern Colorado CURE [Citizens United for Responsibility to the Environment]. 2001. Coal bed methane; Draft regulations before the Las Animas County Planning Commission. SOCOCURE, Bon Carbo, CO. 1 p.; 58 p.

To many, CBM produced water is a valuable by-product in the arid environment of the southwest. However, public interest groups are concerned that CBM water may contain toxic pollutants that may cause long-term damage to humans, animals, and the environment. These concerns led Southern Colorado CURE to prepare draft regulations for consideration by the Las Animas County Planning Commission. The draft regulations are too detailed to annotate but they address several water handling, environmental, and land-use aspects of proposals for CBM development. For example, they suggested that submittal of a development proposal should include: an operating plan; estimated number of site visits by vehicles; a site plan; locations of irrigation ditches within 100 feet of a facility site; a drainage plan; proposed facilities; current surface ownership of proposed facility sites and within ¼ mi of such sites; site boundaries; major geographic features including bodies of water, roads, and utility corridors; existing and proposed access; existing pipeline routes; a weed and disturbance plan; a visual management plan; wildlife mitigation procedures; noise mitigation procedures; performance standards checklist; environmental impact statement report; and produced water disposal plan.

For recording suitability of proposed locations of CBM facilities, Southern Colorado CURE suggested that factors to be considered include noise levels, impacts on air and water quality, vibration and odor levels, fire protection and access requirements, visual impacts, wildlife impacts, and public safety. To assess adequacy of existing roads and access to a site, factors for consideration are: existing and proposed road alignment; intersections; distances from roads to facility sites; traffic volumes and type of traffic; dust control; and existing road uses. To assess site characteristics, factors to consider are topography, natural hazards (landslides, flooding, wildfire), current resource values for open space, corridors, prime farmland, and wildlife habitat.

Stevens, S.H. 1993. Methane from coal deposits technical evaluation and data base (produced water study). Quart. Rev. Methane From Coal Seams Technology 10(4):16-19.

In the San Juan Basin, CBM produced water is disposed of either in deep injection wells or in evaporation ponds. Although the capacity of water disposal facilities has generally kept pace with water production, disposal costs are high (up to $1/barrel). Evaporation ponds are more economical than injection wells, but construction of additional evaporation ponds is subject to local land-use constraints. Advanced Resources International, Inc. carried out an analysis of water production, injection well performance, and potential water treatment technologies in the San Juan Basin. The objectives of this work were to forecast water production in the basin, characterize disposal reservoirs, assess injection completion practices, and analyze the economics of treatment technologies required for surface discharge. This report focuses on the last of these objectives and the main results were as follows:

- Treatment generally is restricted to separation of hydrocarbons, calcium, and other scale-forming ions from produced water. In this study, principles, applications, and unit costs were examined for three water treatment technologies – reverse osmosis, electrodialysis, and ion exchange. In reverse osmosis and electrodialysis permeable membranes separate dissolved solids from water. Ion exchange removes dissolved solids by exchanging water-borne ions for more soluble ions as the water passes through chemical resins. Two other options, distillation and freeze desalination were considered to be uneconomical and were not evaluated.

- Preliminary cost analyses indicate that unit treatment costs for reverse osmosis or electrodialysis could be significantly less than for deep well injection.
- Reverse osmosis is most economical in treating brackish water (100 to 10,000 ppm TDS) but recent membrane developments now allow treatment for water with TDS as high as 35,000 ppm.
- Electrodialysis is an electrochemical separation process in which ions in a dilute solution are electrically transferred through permeable membranes to a concentrated solution. This method is superior to reverse osmosis in dealing with fluctuations in TDS levels that can damage reverse osmosis membranes.
- Ion exchange is not expected to be a primary technology for treating San Juan Basin produced water. This method is used mostly to purify water for drinking or specialized industrial use, or to remove selected scale-forming ions prior to high temperature applications. Ion exchange is competitive with reverse osmosis and electrodialysis only in treating relatively dilute solutions.
- Selective ion exchange may be necessary for lowering born levels to meet agricultural discharge standards but it is not economical for reducing overall TDS levels.
- In the conditions of this study area, the minimum economic scale for surface treatment plants ranged from 5,000 to 20,000 barrels/day but this is highly site specific depending on water chemistry and transportation costs.

TerBest, Jr., H.; Scott, T.R.; Negahban, S.; Gilmer, T.H. 1995. Hydrogeology and methane reservoir behaviour of the Fruitland Formation, Los Pinos River area, Colorado. *In* R.M. Graves and S.J. Thompson, editors. Proc. 1995 Rocky Mountain Symposium on Environmental Issues in Oil and Gas Operations – Practical Solutions for the '90's, Oct. 16-18, Golden, CO. M. Francisco and J. Proud, Proc. editors. Colorado Schl. Mines, Golden, CO. pp. 335-349

An interesting feature of this report is the documented links between natural cycles in precipitation, rates of groundwater recharge, and changes in rates of methane seepage. The report is a result of a study by Amoco Production Company on the hydrogeology and CBM reservoir behavior of the Fruitland Formation in La Plata County, Colorado. The study's main findings were as follows:

- The study indicated the presence of a unique set of hydrogeologic, hydrochemical, and biogeochemical conditions that explain methane seepage in outcrop and subcrop areas.
- Climate of the study area has become generally wetter and somewhat cooler since the late 1950s. The wet periods result in increasing water levels, increasing reservoir pressures, and increasing flow rates in the Fruitland aquifer. Increased flow rates allow more rapid movement of water and dissolved matter from the recharge areas toward the discharge areas. The more rapid flow rates allow reinoculation, faster input of nutrients to the methanogenic bacteria, faster removal of bacterial waste products, and greater rates of biogenic methane generation. The wetter and cooler period was interrupted in the late 1980s and early 1990s by a dry period when both precipitation and runoff were below average. The dry period resulted in significantly less discharge and corresponding natural declines in water levels and pressures.

Reduced pressures result in methane naturally desorbing from coals, which leads to increased concentration of dissolved methane and methane seepage.

- Natural cycles in precipitation continue to have significant effects on recharge to the hinge zone aquifers and their fluid pressures. The dry periods result in pressure declines with methane desorbing from the coal. Wet periods result in pressure increases that allow adsorption of biogenically generated methane (biogas). Biogeochemical research suggests that most CBM in the northern San Juan Basin is biogas.
- Reservoir models show that down-basin production has not contributed to methane seepage in the study area and that gas migration updip to the outcrop and subcrop areas has not occurred. Methane seeps in the subcrop areas result form natural cyclical biologic activity combined with natural cyclical reservoir pressure changes.
- Surface methane seeps were associated with areas of stressed vegetation. Areas now known to have gas seeps and vegetation stress exhibited that vegetation damage in 1960, many years before CBM development. Local residents were aware of these gas seeps since the 1920s.

Triolo, M.; Ogbe, D.O.; Lawal, A.S. 2000. Considerations for water disposal and management in the development of coalbed methane resources in rural Alaska. J. Can. Petrol. Tech. 39(9):41-47.

One current estimate is that coal basins in Alaska contain 28-43 trillion standard cubic meters of coalbed methane. The Alaska Department of Natural Resources estimates that if only 10% of 28 trillion cubic meters is recoverable this methane resource would triple the state’s current proven conventional gas reserves. The authors evaluated several methods of water disposal in terms of applicability to arctic conditions. One case study of water disposal at a recently drilled CBM well in Alaska is also described. Key points of this article include:

- Surface disposal methods are not suited for arctic application. Aside from the shortage of days above freezing, costs of buildings to keep water disposal facilities from freezing are very high. For controlled discharge into arctic streams several design modifications must be made to the aeration and sedimentation ponds. For example, if a mechanical splash aeration pond were used in the arctic, it must be kept from freezing. Also, low temperatures of the fluids in the sedimentation ponds would reduce rates of chemical reaction.
- It is possible that cold weather could be used to advantage, since three freezing processes have been used successfully in pilot projects: 1. The reservoir process involving freezing of large volumes of water – When the ice containing the desired volume of water has been formed, brine below the ice is withdrawn. When the ice melts in spring, it leaves purified water; 2. The layer-freezing process involving freezing of brackish water in successive sheets. The first water melted in warm weather is discarded because it contains most of the impurities. The remaining water is relatively purified; 3. The spray freezing process involving spraying brackish water through a modified lawn sprinkler to form a cone of ice. Pure water is frozen more quickly than brine water and the latter tend to drain away continuously through the winter. In a pilot test of this method in Saskatchewan, chloride content was reduced from 2,000 mg/L to 500 mg/L for 75% of the brackish water. The authors

concluded that surface discharge involving sprinklers would not be acceptable in the arctic but use of freeze-thaw/evaporation processes may hold promise.

- Disposal wells are the most suited method for the arctic environment because they are not dependent on climate, do not require large infrastructure for water treatment, and are relatively easy to design and maintain. Certain modifications should be considered when designing injection wells in arctic conditions. For example, the wellhead and tie-in lines must be kept from freezing and a heated well house is required.
- The multiple effect evaporation process is difficult to apply in the arctic. The method has extremely high capital cost and high operating cost. It would require a huge heated building to keep the necessary equipment from freezing.
- At the time of this article, Alaska's first CBM well near Houston was using a disposal well for handling produced water. The operator, Growth Resources N.L., an Australian company, used a reverse-driven downhole progressive cavity pump that utilized gravity separation to divide the methane and water. Once the co- mingled stream entered the well bore, gravity forced the gas to migrate toward the surface and the water to fall below the production stream, where it was pumped downhole to a thick saltwater coarse-grained conglomerate. In this pilot project the conglomerate was able to accept water faster than it could be produced. The injection pressure was so low that there was no concern about communication between production and injection zones. In this operation, the water never came to the surface and thus water disposal costs were minimal. No treatment of the water was necessary because the formation water had more TDS than the produced water. In addition no transportation of water was necessary since it never left the well bore, and no infrastructure for water storage was required. The only infrastructure needed was a well house to protect the wellhead and the reverse-driven progressive cavity pump. The Houston CBM well was dewatered at the rate of about 500 barrels/day and produced a few thousand cubic feet of methane per day during its dewatering phase. Approximate total cost for the Houston CBM project was $250,000/well for drilling, $50,000 for wellhead equipment, and an operating cost of $1,430/month for supplies and personnel.

U.S. Bureau of Land Management. 2001. Coalbed methane development in the northern San Juan Basin of Colorado: a brief history and environmental observations, a working document. USDI, BLM, San Juan Fld. Office, CO. 1 vol. (various paging).

This report is contained in an informative BLM website (http://oil-gas.state.co.us/blm_sjb.htm). Northern San Juan Basin CBM development is described in terms of: history of CBM well spacing; history of methane seeps; studies of groundwater-entrained methane; BLM responses to environmental concerns; BLM environmental monitoring and baseline data collection; BLM remediation actions; BLM water quality database; environmental monitoring of soils; remediation results; hydrostatically over-pressured CBM wells; water production from the Fruitland Coalbed; and other environmental concerns such as coal fires and hot springs. Some CBM-related environmental observations from the San Juan Basin are listed below:

- Inadequately cemented conventional gas well bores and extraction of produced water from CBM wells are suspected to contribute to natural gas resource losses and to methane migration into surface soils and groundwater.
- As methane production progressed, some residents noticed an apparent increase in occurrence of methane in domestic water wells, while others noticed the presence of gas seeps in pastures, indicated by dead vegetation.
- Where Fruitland coalbeds outcrop, after CBM development there was intensified methane seepage and apparent escalation in hydrogen sulfide levels at historic seepage sites. Stands of stressed and dying trees were aligned with underlying coalbed outcrops. Analyses of the venting gasses in these zones of vegetation mortality showed methane concentrations in excess of the lower explosive limit of methane. Some samples contained over 200 ppm of hydrogen sulfide. Soil oxygen levels were depleted to 0.1% oxygen or less.
- Self-heating of near-surface coal can result from lowering the water table in coalbeds. On the southern Ute Indian Reservation, several coal fires were noted in 1998-1999. This could be a result of both a lowered water table and drawing ambient air into the coalbeds after the water level was lowered, providing oxygen for combustion and resurgence of dormant coal fires.
- Shortly after the onset of CBM production in the late 1980s, a local citizens group voiced concern about increased natural gas contamination of domestic water wells. The U.S. Geological Survey began a study in 1990 that showed measurable concentrations of methane (greater than the detection level of 0.005 mg/L) in 34% of the samples tested, with bedrock wells showing higher concentrations of methane than alluvial wells.
- CBM gas loss through uncemented conventional well bores is of economic importance and gas loss to aquifers and soils is an environmental concern. Groundwater quality degradation may result from a depletion of dissolved oxygen, giving rise to anoxic environments where undesirable sulfate-reducing bacteria can proliferate. Residing in sulfate-rich water, these organisms release toxic hydrogen sulfide.
- Contamination of groundwater by methane was recognized as a concern in 1991 when it was addressed in an environmental impact statement for a proposed 64-well CBM project near Bayfield, Colorado. About 65 water wells were monitored in 1993 and 1996 indicating that no adverse water quality impacts could be detected.
- In 1997 a small hot spring in north Animas Valley exhibited peculiar behaviour with both increased flow rates and increased temperatures over the preceding five years. Association of these changes with CBM development is not specified in this report.
- In summary, in a time span concurrent with CBM production from the Fruitland Coalbed, there have been observations of lowered water tables in domestic and monitored wells, fires in outcrops of the Fruitland Coalbed, occurrence of recently killed vegetation along underlying coal outcrops, and an intensification of naturally occurring methane/hydrogen sulfide seeps.

U.S. Bureau of Land Management, Utah. 1992. Environmental impact statement for the Castlegate Coalbed Methane Project, Carbon County, Utah. U.S. Dept. Int. Bur. Land Manage., Utah. 168 p.

BLM's environmental impact statement (EIS) for the Castlegate CBM project is instructive because it demonstrates how a CBM project was scoped for EIS purposes. For example, the 'project' for the purposes of the EIS involved assessing the impacts of drilling up to 124 new wells with new access roads to each well site. The project area involved 21,450 acres. Pipeline corridors along the access roads would carry gas and produced water pipelines and electrical lines. Gas would be treated and compressed for delivery into a 13.8 mi connector pipeline that would join an existing interstate pipeline. In addition to the proposed project, two project alternatives were defined and evaluated in the EIS: total water disposal by injection wells in which no produced water would be discharged to surface streams; and a no-action alternative in which the CBM proponent would develop its leases on state lands and privately owned lands, and not on lands administered by BLM. Water treatment was proposed to consist of passing about 80% of produced water through an electrodialysis or reverse osmosis system to reduce the dissolved solids content. The remaining 20% water would be discharged to an evaporation pond and then pumped to an underground injection well. Impacts were summarized in relation to: land use; socioeconomic factors; aesthetics (visual resources) and noise; cultural resources; air resources and climate; geological, mineral, and paleontological resources; water resources; soils; vegetation; wildlife; aquatic species; and public safety. The details are not relevant to annotate because they are site-specific for the Utah project area. The concluding section of the EIS focused on short-and long-term impacts, as well as irreversible or irretrievable impacts of the proposed CBM project. Short-term effects were defined as those lasting the life of the project (20-30 years) and long term meant beyond the proposed life of the project. The predicted short-term impacts included some loss of wildlife habitat. It was expected that, after closure, productivity of disturbed areas would be improved because the reclamation plan required revegetation of the site following closure, using species expected to be more productive than those on the site before the project. As a result forage productivity could be increased. Under irreversible and irretrievable effects, it was mentioned that construction of road/pipeline corridors and the well pads would create minor topographic changes to the site. These areas would be recontoured and seeded, but they would remain as minor visual alterations of the area. The vegetation community would be irreversibly changed in species composition. It was also expected that large discharges of treated water into one of the creeks in the project area would physically alter the creek channel, an effect that would be largely irreversible. It was thought that disturbance of sage grouse leks may be an irreversible loss of that resource, although some leks may be used again after closure of the project.

U.S. Bureau of Land Management, Wyoming and USDA Medicine Bow-Routt National Forest. 2000. Scoping summary for the U.S. Bureau of Land Management and USDA Forest Service's Powder River Basin Oil and Gas NEPA analysis and EIS. Buffalo, Casper, and Laramie, WY. 7 p.

This scoping document for an environmental impact statement includes CBM development together with other oil and gas operations. The following environment-related issues are being incorporated into the Powder River Basin oil and gas environmental impact statement: effects of additional development on aquifers in and downslope of the project area; effects on quantity and distribution of surface water in and downstream of the project area; effects on quality of surface water in and down stream of project area and potential to adversely affect current uses of those surface waters; effects on soils; effects on air quality and visibility; effects on vegetation in the project area and in downstream wetlands and riparian areas; effects on wildlife and their habitats; effects on fisheries and aquatic habitats; effects on the project area's ecological integrity and biological diversity; and effects on special-concern species, particularly threatened, endangered, candidate, or sensitive species of plants and animals.

U.S. Environmental Protection Agency, Office of Water. 2000. Proposed coalbed methane study design, an investigation to determine the risks to underground sources of drinking water associated with the hydraulic fracturing of coalbeds for methane gas recovery. Wash., D.C. Doc. EPA 816-K-00-007. 4 p.

In 2000, the U.S. Environmental Protection Agency began a study of environmental risks associated with hydraulic fracturing of coalbeds. EPA initiated the study because of reports from citizens about contamination of their groundwater-supplied drinking water wells, and groundwater loss thought to be a result of nearby hydraulic fracturing in CBM operations. Congressional, state, and industry interest in this issue has recently grown significantly and public opinion on the practices of CBM production has polarized various interest groups. The study design includes: investigation of reported incidents of water contamination or water loss associated with hydraulic fracturing, through interviews with state and local agencies responsible for drinking water protection, citizens, and industries performing hydraulic fracturing; a literature review of fracturing technology and geology in areas developed for CBM production, including information on underlying geology and hydrogeology, current and future water use, underground sources of drinking water, water quality data, CBM well location strategies, water well locations, and associated population levels; review of state and local regulations pertaining to CBM development; and identification of the risks to underground sources of drinking water as a result of hydraulic fracturing of coalbeds. The EPA study schedule called for a draft report to be available for comment in autumn 2001 (with comments solicited on www.epa.gov/safewater/uic/coalbed.html) and a final report to be completed in winter 2002.

Waren, K. 1999. Groundwater assessment, monitoring, and reporting recommendations for coalbed methane operations. Memorandum to J. Stults, Administrator, Water Resources Division, Montana Dept. Nat. Resour. Conserv. 4 p.

The author, a hydrologist with Montana's Water Management Bureau, indicated that the type of hydrologic assessment and monitoring needed for a particular CBM project is best determined on a case-by-case basis. He emphasized that hydrogeologists must be involved in assessing the targeted coalbeds and in determining a monitoring scheme. A qualified review board, with expertise in both hydrogeology and CBM operations, was recommended for groundwater assessment and monitoring plans. This memorandum made the following points to characterize the type of assessment and monitoring that should be used to track groundwater conditions near CBM operations.

- Hydrogeologic conditions must be evaluated before CBM pumping is initiated. Such evaluation should include maps of the natural potentiometric surface of the targeted coalbed, an assessment of existing wells, springs, and streamflow that could be impacted by the operation. This pre-operational inventory should be conducted on all wells and springs within at least 3 mi of the outer bounds of the proposed CBM operation. The inventory of wells should include basic data such as owner, location, static water level, depth to water, well log if available, and specific conductance.

- In an area to be tested or developed for CBM, a group of test wells could be drilled at a density of 1 per section to determine the potentiometric surface elevations in the coalbed. These wells can later be converted to methane extraction wells.
- Dedicated monitoring wells should be placed outside the operating area. For each targeted coalbed, a minimum of four such monitoring wells should be drilled in four different directions from the proposed project. The orientation of the four wells should be shifted to align with the predominant potentiometric surface gradient.
- In addition to the four dedicated coalbed monitoring wells, at least one other dedicated well should be drilled to assess baseline conditions in the first significant aquifer both overlying and underlying the coalbed.
- For larger projects, more than four monitoring wells would be needed. The monitoring network should include wells outside the operating area to a distance of up to 2 mi from the nearest CBM well, and such wells should be placed so that nowhere along the periphery of the operations does the distance between dedicated monitoring wells exceed about 4 mi.
- The coalbed structure should be compared with topography of the area to determine if and where the coal crops out or contacts alluvium in the area, regardless of distance from the CBM operation. Any such contact areas should be evaluated to determine whether water pressure reductions could impact springs or groundwater discharge areas.
- Pre-project baseline water quality tests should be conducted for the peripheral monitoring wells and for the aquifers that lie above and below the coal seam. After operations begin, groundwater quality samples should be taken in the dedicated monitoring wells to determine if CBM operations are changing water quality in the coal. This sampling could be infrequent, perhaps every two years unless a significant problem is suspected.
- In addition to the dedicated monitoring wells, any existing wells with 3 mi of a CBM project and completed in the same coal seam should be considered potential monitoring locations. As a guideline, existing wells a few miles apart should be sufficient for additional monitoring points, subject to expansion to a bigger sampling area if problems are found.

Warrance, N.; Bauder, J.W. 2001. A look at CBM product water reinjection. *In* Montana State University, Dept. of Land Resources and Environmental Sciences, Bozeman, MT. Water Quality and Irrigation Management, Position Pap. 8 p.

The coal seams are aquifers in southeast Montana and there is concern that CBM removal of water from these aquifers will adversely affect springs and streams used for irrigation, drinking water, and livestock wells. One option proposed to deal with CBM produced water in the Powder River Basin is to re-inject it into the coal aquifers. Injection of CBM water is a common practice in the southwest United States but there it is typically injected into deeper formations below the coalbeds rather than into the original coal seam. This report is a synopsis of questions and resulting comments about CBM water reinjection, based on responses from: John Wheaton, Hydrogeologist, Montana Bureau of Mines and Geology; Steve Custer, Geologist, Montana State University; George Hudak, Underground Injection Control Manager, Montana Board of Oil and Gas; and Terry Dobkins, Vice President, Production, Pennaco Energy, Inc. Highlights of their professional opinions are given below.

- CBM producers do not totally dewater a coal seam; they lower the hydrostatic pressure (or head of water) in the coal seam to just above the top of the seam. It is essential that some water movement occur in the coal seam to encourage gas migration toward the well. To calculate the acceptable and feasible distance between reinjection wells and producing wells that terminate in the same coal seam, it is necessary to calculate the drawdown distance for the CBM field and the sphere of influence of the reinjection pressure mound for the reinjection field. It reduces the efficiency of the extracting process if the producing and reinjection wells are too close to each other; it would essentially be like emptying and filling a bucket at the same time.
- The impact of reinjection on the production field is a site-specific problem that depends on local aquifer characteristics, location of injection wells, and quantities and qualities of reinjection water.
- The unexpected or unpredictable consequences of injecting CBM product water to other aquifers may present more challenges than finding alternative sustainable uses for the water.
- Opinions differ about the time it will take to recharge depleted coalbed aquifers. In coal mining areas recharge can occur within five years or less but this is typically for small areas where open pit or strip mining involves only a few square kilometres. In contrast, with CBM extraction the area of groundwater impact may be as large as a township. In the large geographic areas impacted by CBM extraction, there may not be enough water left after production to significantly recharge the groundwater system.
- There are differences of opinion about movement of surface-discharged CBM water back into aquifers. Some industry representatives have stated that almost all CBM water discharged to the land surface eventually reaches underlying aquifers. Montana State University scientists contend that more likely almost none of the discharged water returns to the aquifers from which it was pumped, but goes instead to recharging shallow alluvium and coarse soil aquifers less than 60 m deep, or is lost to evaporation. What actually happens to surface discharged water is very site specific. In some places discharge to holding ponds is known to percolate to the water table.
- Some specialists believe that reinjection intake rates will typically be lower than withdrawal rates, but that depends on the site. Each setting is different and needs to be assessed with conceptual models and good geologic, hydraulic, and soils information.
- It is suggested that instead of drilling new water wells if CBM extraction causes wells or springs to dry up, one or two CBM wells could be left in place when gas extraction ceases and these wells could be converted to domestic use wells until natural recharge replenishes supplies to springs and wells as existed before CBM extraction.

- Montana State University is undertaking wetlands research to find ways to reduce total dissolved solids and sodium adsorption ratios in CBM water, using salt tolerant plants and infiltration wells that are integrated into wetland systems.
- Injecting water is expensive and can involve several alternatives: pumping to deep aquifers to dispose of the water; pumping to shallow aquifers making the water available for local use; and pumping to the coalbed that was dewatered. Issues that need to be addressed when considering alternatives include economics, chemical compatibility of the injected water with the recipient geological formation, and fate of the water.

Warrance, N.; Bauder, J.W. 2001. Reinjection technology – process and applications, including disposal of CBM product water. *In* Montana State University, Dept. of Land Resources and Environmental Sciences, Bozeman, MT. Water Quality and Irrigation Management, Position Pap. 14 p.

Whether or not CBM-produced water can be reinjected into the original coal seam or if it must be injected to a shallower or deeper aquifer is a question currently under debate in the Powder River Basin. Injection to an aquifer other than the source coalbed aquifer is the preferred method outside the Powder River Basin. Some highlights of the authors' review are:

- A concern of environmentalists and local residents in southeastern Montana is that drawdown of local and regional aquifers could reduce or eliminate crucial groundwater and surface water supplies.
- Because it is mechanically easier to inject into a shallower or deeper aquifer, and this clearly does not affect methane extraction, there has been little incentive for industry to investigate reinjection into source coal seams. Only recently, with concern about reducing water levels in coal seam aquifers, has there been serious consideration of reinjecting water back into source coal seams.
- Cost is major obstacle to widespread reinjection of CBM produced water in Wyoming. In addition to cost, a further deterrent to reinjecting water into the producing coal seam is the difficulty of forcing water into a system that may still be saturated. One alternative to injection mentioned is the use of large holding pits connected to infiltration wells.
- A key step is to determine the critical distance between producing wells and reinjection wells so that the respective drawdown and recharge fields do not significantly overlap. If such wells are too close to each other, reinjected water will likely reappear as produced water. Further testing is necessary to determine if producing and reinjection wells can be placed far enough apart so that they do not effectively cancel each other out.
- A challenge with reinjection is that it is difficult to predict where water will go once it enters the ground. The capacity of individual aquifers and how they are connected is not well understood. The authors give the example of companies that are injecting CBM discharge water by simply pumping until they can no longer get additional water into the ground.
- If produced water can be placed into an already depleted aquifer, the process is much more feasible. For example Pennaco is reinjecting water into an aquifer that has been drawn down for 60 years and which now supplies water for the city of Gillette,

Wyoming. For the Gillette injection well system, which receives water from seven CBM production wells, construction costs were about $1 million, and maintenance costs are about $0.01/barrel, or $625,000/year.

- If CBM drawdown causes streams used for irrigation and drinking or livestock wells to dry up, injecting into an aquifer beneath the coal seam will likely do nothing to restore these surface water sources. To make this deeper water accessible, the CBM industry may be required to develop deeper wells after gas production ceases to ensure that local residents have a usable water source.
- Because most of the drinking wells in southeastern Montana come from either coal seams or aquifers above the coal seams, some specialists urge that reinjection is the only way to preserve the hydrostatic balance in coalbed aquifers. However, many engineers involved in CBM production argue that this would defeat the idea behind drawing down the pressure to release CBM gas that is adsorbed to the coal's surface by water pressure. A possible compromise would be to inject water into a lower formation at the onset of drilling in order to achieve the necessary water pressure reduction in the coal seam, and then reinject water into the coal seam later on. This approach would work only if the deeper aquifer is not already saturated.
- Subsidence is a concern in areas where groundwater levels have dropped dramatically, particularly in urban areas where subsidence of only a few centimeters may cause structural damage. Subsidence was an initial concern in relation to CBM development but current projections indicate that water withdrawals are not likely to cause subsidence in the Powder River Basin.
- A conclusion is that the two main problems associated with CBM mining, aquifer drawdown and saline/sodic waters that are questionable for surface discharge, can both be solved through injection or reinjection of produced water. The soil structure problem caused by high-sodium water is avoided if water is not applied to the land surface. However, aquifer drawdown may still be an issue particularly in areas where a high density of producing CBM wells makes reinjection into the coal seam difficult. There are sufficient uncertainties associated with reinjection of CBM product water back into the source coalbed aquifers to justify additional research and modeling of reinjection dynamics.

Way, S.C.; McKee, C.R.; Bell, G.J.; Brandenburg, C.F. 1983. Role of hydrology in the production of methane from coal seams. Quart. Rev. Methane From Coal Seams Tech. 1(2):13-19.

Even before the time of this article, extraction of methane from coal seams had been pursued for many years. This extraction was initially for safety purposes in underground coalmines and gave little attention to the hydrology of coal seams. When methane removal was commercially pursued independently of coal mining, conventional gas exploration and production methods were used. Production methods for conventional gas do not normally involve dewatering. In contrast, when a CBM well is pumped the head or pressure of the reservoir is reduced in the vicinity of the well bore. As pumping continues more methane is desorbed, and as dewatering increases the rate of gas production also increases. This results in a negative decline curve that is a fundamental difference from production of conventional gas from sand strata. Over time, methane production starts to decline but not as steeply as gas production in a conventional gas well. Many areas have been found where the coals are only partially saturated, but in some cases the coals are overpressured and cause gas 'kicks' or even blowouts when they are penetrated.

This article contains an informative summary of fundamentals of regional hydrogeology, hydrology of coalbeds, and hydrology in the zone of influence of well bores including: hydrologic relations between the ground surface, confined aquifers, impermeable strata above and below confined aquifers, piezometric surfaces, and drawdown curves (the cone of depression of the piezometric surface). The authors emphasize that hydrologic characterization should be a part of any CBM field program. Such tests are needed to decide on the correct dewatering technique. Knowledge of the hydrologic properties also allows design of well features and the well field spacing pattern.

Witherbee, K.G.; Salwerowicz, F.A.; Hoffman, K.L. 1992. Environmental and regulatory aspects of the management of coalbed methane development and production, northern San Juan Basin, Colorado. *In* R.K. Singhal, A.K. Mehrotra, K. Fytas, and J-L. Collins, editors. Environmental Issues and Management of Waste in Energy and Mineral Production, Proc. 2nd Intern. Conf., Sept. 1-4, 1992, Calgary, AB. A.A. Balkema, Rotterdam, Neth. Vol. 1, pp. 103-110.

This article by representatives of the Bureau of Land Management, Colorado State Office, was in response to concerns by the San Juan Citizens Alliance and the Western Colorado Congress. Removal of water from the Fruitland Formation resulted in concerns about disposal of produced water, potential depletion of groundwater from near-surface aquifers and migration of liberated methane into adjacent aquifers. Most of the specific concerns focused on contamination of aquifers and disposal of produced waters as a result of CBM operations. There was also concern for safety of persons working around produced water storage and treatment facilities because of suspected naturally occurring radioactive materials in produced water. This article describes the initial phase of a BLM study that focused on gathering published and unpublished information and identification of potential impacts from current accepted practices in CBM exploration and development. Gas production in the northern San Juan Basin produces small quantities of water when compared to the amount produced in CBM operations. Prior to CBM development most of this produced water was disposed in surface evaporation pits, and it was continuation of this practice that raised concern for the larger quantities of water involved in CBM operations. The study also noted the contrast between conventional gas exploration that involves the deeper central portion of the San Juan Basin versus the CBM development which was occurring mainly at the margins of the basin, involving shallower wells with closer affinity to groundwater aquifers when compared to deeper natural gas wells.

Wyoming Department of Environmental Quality. 1999. Authorization to discharge produced water from coal bed methane wells under the National Pollutant Discharge Elimination System (NPDES). 25 p.

Among the detailed data collection requirements specified in this Wyoming authorization, the following could be applicable in other jurisdictions:

- The quality of effluent discharged by the facility shall, at a minimum, not exceed the following limits: total petroleum hydrocarbons - 10 mg/L; total dissolved solids –

5000 mg/L; pH – 6.5 to 8.5 SU; sulfates – 3,000 mg/L; chlorides – 46 mg/L; specific conductance – 7500 µmhos/cm; radium 226 – 1pCi/L; total iron – 60 µg/L; total manganese – 10 µg/L; and total barium – 100 µg/L.

- The Notice of Intent must include, among other things, "… a description of the erosion control measures that will be implemented to prevent significant damage to or erosion of the receiving water channel at the point of discharge".
- "All waters shall be discharged in a manner to prevent, at the point of discharge, erosion, scouring, or damage to stream banks, streambeds, ditches or other waters of the state. … In the case where produced water discharges are causing damage to land and/or vegetation due to diffuse or 'spread' flow, the state reserves the right to require that the discharge be confined to a channel, pipe, or other conduit."

Wyoming Game and Fish Department. n.d. Creating wetlands for wildlife with coal bed methane water. Sheridan, WY. Pamphlet.

Landowners and CBM developers sometimes have the opportunity to create new wetlands of value to waterfowl and wildlife. Practical suggestions in this pamphlet are as follows:

- CBM discharges may provide year-round flows that can fill reservoirs. Dams and spillways may need to be improved to handle the increased flow of water.
- The discharge into the reservoir should be as close as possible to the high water line, because water flowing down draws picks up silt that reduces the life of the impoundment. Rocks should be placed at the discharge point to aerate the water.
- Year-round discharge will impede ice formation on a reservoir so fencing to limit livestock in winter will reduce accidental losses of livestock.
- If several small (1-2 acre) ponds are initially planned, consider piping this water to make a larger wetland complex (5-20 acres). Along the water pipeline route livestock watering tanks can be located.
- Game and Fish Department guidelines are available for design of shorelines, spillways, overflows, islands, and vegetation establishment around reservoirs to create optimal wildlife values.
- For fish production, water bodies should be at least 1 acre in size and at least 15 feet deep over 25% of the water area to prevent winterkill of fish and to discourage excessive growth of aquatic vegetation in shallow water.

Wyoming Game and Fish Department. n.d. Wildlife habitat considerations for coal bed methane development. Sheridan, WY. Pamphlet.

Landowners and CBM developers can obtain practical advice from this pamphlet on how to use CBM activities to protect and enhance wildlife habitats, including the following suggestions:

- Where possible, new roads should be planned away from draws, creeks, and other drainages.
- Consider placing new roads adjacent to fences or other natural breaks in the landscape to reduce disturbance to wildlife and livestock.
- If CBM development is planned near grouse leks, electrical lines should be buried to avoid creating perches for hawks and eagles that are predatory on grouse. Drilling

and pipeline activity should be encouraged outside the breeding season for grouse (1 March – 15 May).

- For reclaiming roads, drill sites, and pipeline rights-of-way, native grass and forb species should be used and noxious weeds should be controlled.
- If CBM pipeline corridors must intersect riparian zones or streams, the crossing should be at right angles to minimize the area of disturbance.
- If CBM water is considered for crop irrigation, soils and water should be tested for compatibility with irrigation.

Wyoming Outdoor Council and Powder River Basin Resources Council. 2001. Coalbed methane development in Wyoming's Powder River Basin: natural gas development and its threats to the landscape, people and wildlife. Lander, WY. 1 vol. (various paging).

This well illustrated website article provides observations, opinions, and concerns from the perspective of public interest groups in Wyoming. Key topics covered are: an overview of key issues in CBM development in the Powder River Basin; risks to the landscape, people, and wildlife in the basin; handling CBM produced water; and noise, aesthetic concerns, and cumulative effects of power lines, compressor stations, roads, well pads, drilling rigs, and machinery; unintended consequences of methane migration.

The authors provide estimates of produced water yields when coal seams in the Powder River Basin are dewatered. The average CBM well pumps 15 gals/min and in Wyoming, unlike most CBM fields in Colorado, this water is not reinjected into aquifers. In many places in the Powder River basin produced water can reach levels as high as 100,000 gals of water per day from each well.

Following are the key concerns expressed by both councils:

- Unknown impacts on wildlife and fisheries as a result of the massive amounts of discharged water;
- Soils in the basin are highly erodible and the increased water flow can, and has, caused serious erosion and soil loss;
- Arroyos and gullies, which are normally dry much of the year and which provide the best forage for wildlife and livestock as well as shelter for newborn calves, will be disrupted when inundated by discharge of CBM produced water;
- Most of the low quality CBM water will flow north to Montana or east to South Dakota, possibly lost forever from Wyoming's natural aquifers;
- From 1986 to the time of this report, over 30 billion gallons of high salinity water had been produced and dumped onto Wyoming's land surface during CBM dewatering. The authors estimate that local aquifers that are losing this water may take up to 1000 years to gain back the lost water supply. The water wells of ranchers in the basin have and will continue to go dry due to this massive dewatering.
- The authors contend that the Wyoming Department of Environmental Quality is illegally administering the Clean Water Act as it is allowing degradation of existing water quality and jeopardizing uses of Wyoming's surface waters. Of particular concern is the high salinity of the CBM produced water which poses a threat to

native and irrigated vegetation, in addition to harming soils and allowing invasion of salt-tolerant weeds;

- There is also concern that to date no studies have been undertaken by BLM or any state agency concerning the impacts of millions of gallons of CBM produced water on fisheries or aquatic life;
- These public interest groups conclude that CBM extraction is a very serious threat to people and the environment in the Powder River Basin. Not only does it carry impacts associated with traditional natural gas development (miles of roads and pipelines, and many well pads and compressor stations) but also the discharge of poor quality produced water.
- The authors urge that every effort be made to thoroughly study and publicly disclose the likely CBM impacts prior to, and not after, full field development.

Zander, R.A. 1999. Development, environmental analysis, and mitigation of coal bed methane activity in the Powder River Basin of Wyoming. *In* 1999 International Coalbed Methane Symposium, 1999, Tuscaloosa, AL. Univ. Alabama, Tuscaloosa, AL. pp. 47-57.

When the Rawhide Butte subdivision in Wyoming had to be abandoned in 1987 because hydrogen sulfide and methane were seeping into house basements, the first serious attempts to develop the CBM resource began. The author, Bureau of Land Management, described the evolution of National Environmental Policy Act (NEPA) analyses carried out by BLM since 1989. Initial BLM stipulations were as follows: BLM would work with private landowners, industry, and others to find beneficial uses of discharged CBM water; surface discharge would only be allowed into well-developed, stable, stream channels; cumulative maximum discharge would not exceed the annual naturally-occurring peak flows; instream structures would be used to reduce the energy gradient and prevent accelerated channel erosion; if channel degradation occurred, discharge points would be moved downstream or to another channel; operators would be required to provide alternative sources of water to compensate surface owners who lost water because of CBM operations; surface disturbance in important wildlife habitat would be minimized; visual resource would be protected; and altered streamflows would be planned to protect the requirements of livestock.

For one CBM project in 1992, a network of 12 water wells was established in Wasatch sands above the coal to: ensure no unacceptable impacts to quantity or quality of groundwater aquifers supplying local water wells; supply baseline data to evaluate success of the proposed operations; and provide information to estimate impacts of future CBM operations in the Powder River Basin. In another project, major identified issues dealt with the impacts of water level drawdowns in water wells, potential leakage of water from aquifers located above coal beds, potential migration of methane to shallow aquifers or to the surface, potential impacts to coal mine monitoring wells, determination of which industry (coal mining or CBM) was responsible for the drawdown; and the possibility of increased erosion due to surface discharge. To address the concerns of water drawdowns, an extensive monitoring plan was designed to detect: a lowering of head; a change in water quality; and a change in amount of methane produced in a given well. An assumption made in the early environmental assessments was that overlying and underlying shales serve as confining layers for the coal that holds water and methane in place. This same assumption implied that water would not migrate from aquifers located above or below the coal. Wells that have been continuously monitored since 1992 have confirmed the validity of this assumption.

To monitor amounts of streamflow, extra surface water measurement stations were established. Channels receiving discharged water were monitored for signs of accelerated erosion. BLM urged companies developing large CBM projects to hire qualified hydrologists to manage their water discharge programs. In relation to groundwater, BLM recognized that much groundwater monitoring data was already available from operators and state and federal agencies. These data allowed development of a common database and estimation of actual drawdown curves as a result of CBM water removal.

In addition to concerns about groundwater depletion, surface water discharge, beneficial uses of produced water, and coal-CBM development conflicts, air quality became an additional issue because of the large number of compressors needed to move the methane to market. BLM responded by analyzing cumulative air quality impacts from all sources in the Powder River Basin. The draft environmental impact statement for the Wyodak CBM project also expanded the social-economic analyses as it became apparent that CBM development would have a significant impact on both employment and economic benefits.

Zhao, Q.; Li, W.; Sun, F.; Chen, M. 1997. Coalbed methane occurrences in China and evaluation of favorable areas. *In* 1997 International Coalbed Methane Symp., May 12-17, 1997, Tuscaloosa, AL. Univ. Alabama, Tuscaloosa, AL. pp. 345-349.

This article indicates that the amount of produced water can vary substantially depending on the type of coalbed involved. For example, the CBM basins in China are divided into four types:

- Artesian water-blocked type – In this type meteorological water and aquifers above and below the coal seams are combined to form high hydrodynamic flow, while water flow in the coal seams is limited and weak.
- Roof water micro-infiltration blocked type – In this type the roof of coalbeds is sandstone or carbonate aquifer in which water infiltrates along cleats or fractures, and hydrodynamic control is weak.
- Trapped type – In this type the CBM pool is formed in a structural trap, usually associated with low amounts of produced water because little or no water exists in the coalbeds.
- Pressure-sealed type – This type is generally associated with a free methane pool so that large quantities of water are not involved.

Zimpfer, G.L.; Harmon, E.J.; Boyce, B.C. 1988. Disposal of production waters from oil and gas wells in the northern San Juan Basin, Colorado. *In* J.E. Fassett, editor. Geology and Coal-bed Methane Resources of the Northern San Juan Basin, New Mexico and Colorado, 1988 Coalbed Methane Symposium. Rocky Mtn. Assoc. Geol., Denver, CO. pp. 183-198.

Several environmentally acceptable and economically sound brine conveyance and disposal alternatives have been assessed in the northern San Juan Basin. Brine conveyance should be viewed separately from brine disposal. Two brine conveyance alternatives, truck and pipeline transportation, are available. Once brine is moved to a desired site for disposal, four alternatives are available: direct use of brine without treatment; direct use after treatment to improve water quality; disposal in evaporation pits; and underground injection. The advantages, disadvantages, and costs of either conveyance alternative are independent of the brine disposal alternatives. Either conveyance alternative can be combined with any of the four brine disposal alternatives.

Pipeline transport of produced water has fewer disadvantages than truck transport, although a pipeline system is initially more difficult to implement because of planning, design, and capital costs. Over the long term, pipeline transportation is less expensive on a unit cost basis and provides less environmental risk than truck transport of water.

On-site direct use of brine without treatment is the least expensive disposal alternative but is limited to areas with relatively good water quality. Treatment prior to discharge is generally too costly to justify. Unlike other disposal alternatives, the cost of direct use is generally not a function of volume of brine, so there is no economy of scale to be considered. At the time of this article, the cost to dispose of brine by direct on-site use was less than $0.01/barrel when irrigation water users in Colorado were paying between $0.005 and $0.01/barrel. For brine with a quality suitable for irrigation or stock watering, on-site direct use is the least costly disposal alternative.

Evaporation pits have relatively large land requirements, high capital start-up costs, and are often subject to environmental problems. However, passive pits have low energy consumption needs. Injection wells also have high start-up costs, may require on-site brine storage, and may not be suitable for disposal of small volumes. In general, for brine disposal volumes below about 30,000 barrels of water per day per facility, injection well disposal is less expensive than evaporation pit disposal. Geological variables and cost factors that determine feasibility of underground injection disposal include: formation porosity; formation permeability; effective thickness of formation; formation hydrostatic pressure; brine injection capacity; depth to base of deepest freshwater sand; disposal well depth and cost; wellhead equipment cost; cost of well integrity testing; and cost of well injectivity testing. The authors quantified the desired geological variables of the receiving formations and the estimated costs as of 1998, but these figures are not annotated because they may not be applicable to current costs and conditions in other coalbeds.

No single disposal method is appropriate for all situations. Successful disposal systems must be designed on the basis of operational concerns, economics, environmental factors, and regulatory requirements. The authors recommended that different operators developing adjacent CBM properties should consider establishing central brine disposal units. The potential economic advantage of large-volume disposal may be substantial, however difficult the coordination between different CBM operators may be.