WYOMING STATE GEOLOGICAL SURVEY
Ronald C. Surdam, State Geologist

COALBED NATURAL GAS CONFERENCE: I—RESEARCH, MONITORING, AND APPLICATIONS

edited by
Jaime R. Stine

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Laramie, Wyoming
2005

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Front cover: A pond and wetland area created from discharge water associated with coalbed natural gas production in the eastern Powder River Basin, Wyoming. Photograph by B.J. Kristiansen, courtesy of the Wyoming Coalbed Methane Coordination Coalition.

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Introduction

Conference overview

Coalbed Natural Gas Conference: I—Research, Monitoring, and Applications

August 17-19, 2004

Wyoming Union, University of Wyoming

Laramie, Wyoming

In response to federal, state, and local agency requests to learn about and share information on current research and monitoring projects related to various aspects of coalbed natural gas (CBNG) development in Wyoming and the West, the University of Wyoming's Ruckelshaus Institute of Environment and Natural Resources convened a steering committee (see list of members below) to guide the organization of the First Annual Coalbed Natural Gas Research, Monitoring, and Applications Conference. The steering committee was comprised of state and federal agency personnel, University of Wyoming faculty, industry and environmental representatives, and non-governmental organizations involved in CBNG research and management.

The conference took place from August 17 through August 19, 2004 at the University of Wyoming campus in Laramie. It opened with agency and organization presentations on CBNG development and their roles, perspectives, and research associated with the development. Robbie Roberts, Environmental Protection Agency Region 8 Administrator, delivered a keynote address at lunch, then participants attended four sessions emphasizing research and/or monitoring programs that have near-term applications to: 1) surface and ground water quality and quantity, 2) well completion, monitoring, and produced water treatment, 3) water use, soils and wildlife, and 4) information management, risk assessment, and legal issues. A poster session ran concurrently. The final day of the conference was arranged as a workshop discussion among invited researchers and others emphasizing near-term and longer-term applications of the research and monitoring programs presented during the conference.

Nearly 300 attendees from around the U.S. and Canada gathered at the conference. Backgrounds and interests varied from local, state, and federal government to representatives from academia and from ranching to environmental advocacy. During the three days, over 50 reports were presented in oral or poster format. The following proceedings represent the content of the conference and ideas that arose from the workshop discussion on the final day.

Steering Committee members and affiliations

Gary Beach, Wyoming Department of Environmental Quality

Harold Bergman, Ruckelshaus Institute of Environment and Natural Resource

Lance Cook. former Wyoming State Geologist, Wyoming State Geological Survey

Carol Frost, UW Geology Department

Diana Hulme, Ruckelshaus Institute of Environment and Natural Resource

Jim Gazewood, Bureau of Land Management

Don Likwartz, Wyoming Oil & Gas Conservation Commission

Jill Morrison, Powder River Basin Resource Council

KJ Reddy, UW Renewable Resources Department

John Robitaille, Petroleum Association of Wyoming

Mickey Steward, Coalbed Methane Coordination Coalition

Ron Surdam, Wyoming State Geologist, Wyoming State Geological Survey

John Wagner, Wyoming Department of Environmental Quality

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University of Wyoming Research Office

Wyoming Department of Environmental Quality

Wyoming Oil and Gas Conservation Commission

Wyoming State Geological Survey

Wyoming State Office of the Bureau of Land Management

Environmental Protection Agency Region 8

Coalbed Methane Coordination Coalition

Powder River Basin Resource Council

Petroleum Association of Wyoming

Western Governors' Association

With additional financial support from

WellDog, Inc.

Agenda

Tuesday, August 17, 2004–Wyoming Union, Yellowstone Ballroom

9:00 a.m. University welcome–UW Vice President for Research Bill Gern

9:10 a.m. Welcome, introductions, and conference overview–Harold Bergman, UW Ruckelshaus Institute of Environment and Natural Resources and Gary Beach, Wyoming Dept. of Environmental Quality

9:20 a.m. Overview of CBNG development in Wyoming–Rod DeBruin, Wyoming State Geological Survey and Don Likwartz, Wyoming Oil and Gas Conservation Commission

Explanation of the resource quantity and distribution and briefly discuss the history of development and current trends.

9:50 a.m. BREAK

10:15 a.m. Panel review: Agency and organization perspectives on research and monitoring needs

- Alan Kesterke, Wyoming State Office of the U.S. Bureau of Land Management
- John Corra, Wyoming Department of Environmental Quality
- Don Likwartz, Wyoming Oil and Gas Conservation Commission
- Harry LaBonde, Wyoming State Engineer's Office
- Jill Morrison, Powder River Basin Resource Council
- John Robitaille, Petroleum Association of Wyoming
- Paul Orbuch, Western Governors' Association

Perspective on future research, monitoring and technology transfer needs to sustain CBNG development in an environmentally sound manner. This panel discussion will help set the stage for discussions on August 19th.

11:30 a.m. Keynote presentation and buffet lunch, Wyoming Union Yellowstone Ballroom–Robbie Roberts, EPA Region 8 Administrator

1:00 p.m. **Session 1*: Surface and Ground Water Quality and Quantity–Wyoming Union Yellowstone Ballroom**–*Co-Chairs: John Wagner, Wyoming Department of Environmental Quality and Carol Frost, University of Wyoming*

Wednesday, August 18, 2004–Wyoming Union, Yellowstone Ballroom

8:00 a.m. **Session 2*: Well Completion, Monitoring, and Produced Water Treatment–Wyoming Union, Yellowstone Ballroom**–*Co-Chairs: Dennis Lamb, Wyoming Dept. of Environmental Quality and KJ Reddy, University of Wyoming*

12:10 p.m. Lunch break–on your own

1:30 p.m. **CONCURRENT SESSION–Session 3*: Water Use, Soils and Wildlife–Wyoming Union, Yellowstone Ballroom**–*Co-Chairs: Richard Zander, US Bureau of Land Management and Larry Munn, University of Wyoming*

*Poster session will run concurrently with oral presentations

1:30 p.m. **CONCURRENT SESSION–Session 4*: Information Management, Risk Assessment and Legal Issues–Wyoming Union, Family Room**–*Co-Chairs: Gary Beach, Wyoming Dept. of Environmental Quality and Jeff Hamerlinck, Wyoming Geographic Information Science Center*

5:00 p.m. Conference adjourns for the evening

Thursday, August 19, 2004–Wyoming Union, Family Room

9:00 a.m. Plenary Discussion of Conference Topics

9:30 a.m. Breakout group discussions–facilitated by Session Co-Chairs

Session 1: Surface and Groundwater Quality and Quantity (Ballroom West)

Session 2: Well Completion, Monitoring, and Produced Water Treatment (Ballroom East)

Session 3: Water Use, Soils, and Wildlife (Union Senate Chambers)

Session 4: Information Management, Risk Assessment, and Legal Issues (Ballroom Center)

12:00 p.m. Lunch Break–on your own

1:00 p.m. Plenary Brainstorming Session, Wyoming Union Family Room– facilitated by Harold Bergman, UW Ruckelshaus Institute of Environment and Natural Resources and Gary Beach, Wyoming Dept. of Environmental Quality

Breakout groups will return to the plenary group, report on their discussions and make recommendations on each breakout topic.

2:00 p.m. Steering Committee Compilation and Prioritization of Research, Monitoring and Applications Needs, Wyoming Union Family Room– facilitated by Harold Bergman, UW Ruckelshaus Institute of Environment and Natural Resources and Gary Beach, Wyoming Dept. of Environmental Quality

Breakout findings with potential near-term applications to development, monitoring, and regulation will be compiled and prioritized.

2:45 p.m. Last Thoughts and Closing Remarks–Gary Beach, Wyoming Department of Environmental Quality and Harold Bergman, UW Ruckelshaus Institute

3:00 p.m. Conference and Workshop adjourn

*Poster session will run concurrently with oral presentations

Overview of coalbed natural gas development in Wyoming

Rodney H. De Bruin, Wyoming PG-3045–Wyoming State Geological Survey, Laramie, Wyoming

Wyoming is fortunate in that it has more coal than any of the other lower 48 states and that most of the state's sedimentary basins have substantial coal deposits. Bituminous and subbituminous coal beds occur in all 10 coal fields of the state (**Figure 1**). These coal beds are early Tertiary and Late Cretaceous in age and contain both biogenic and thermogenic coalbed natural gas (CBNG).

To date, most CBNG development has taken place in the Powder River Coal Field of northeastern Wyoming. The existence of CBNG in this coal field was known since 1916 (Jones and De Bruin, 1990), but commercial development did not begin until 1987. That year, natural gas from a coal bed was detected seeping into a subdivision north of Gillette, Wyoming, and a company began producing coalbed methane from

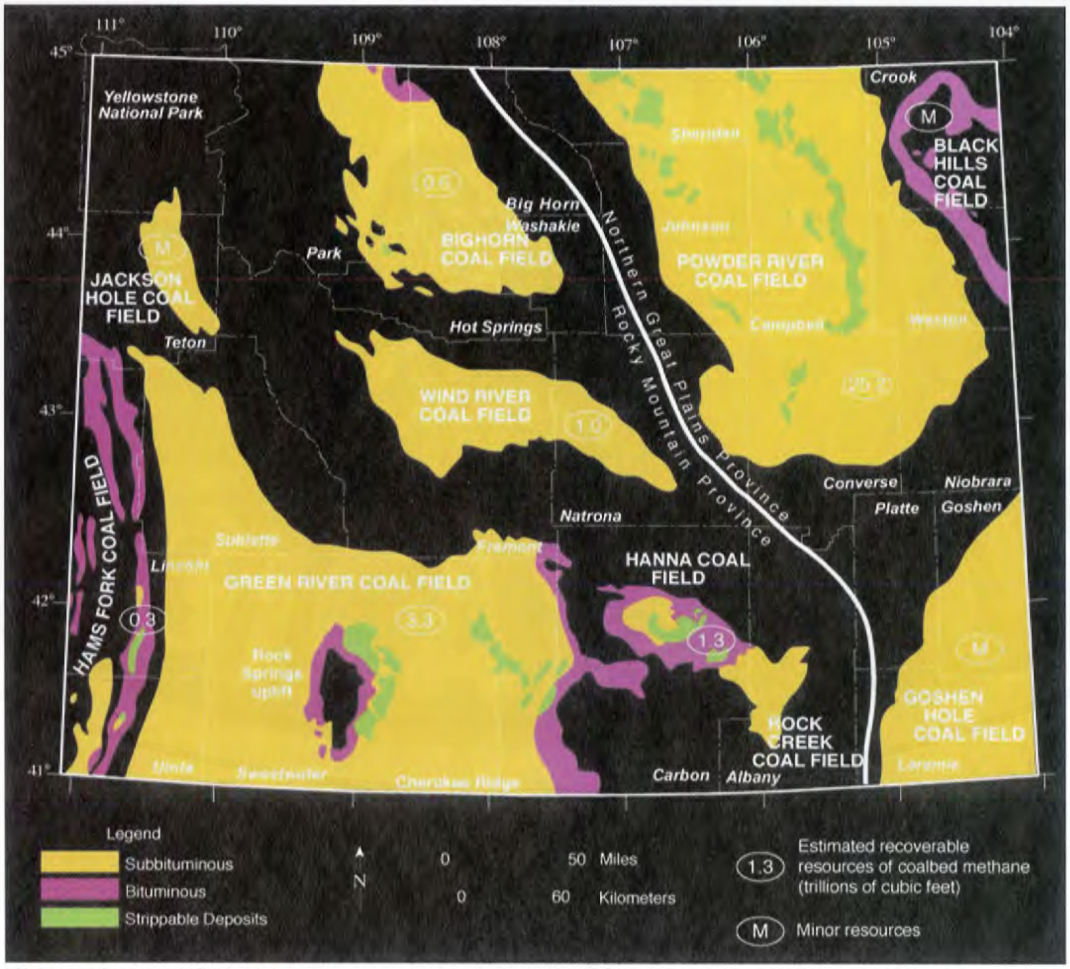

Figure 1. Coal fields and rank of coal in Wyoming, showing estimated recoverable coalbed natural gas (trillions of cubic feet, TCF) in each field. Coal field map modified from Glass, 1997.

nearby monitoring wells. Section 29 tax credits passed by the U.S. Congress pertained to CBNG production and helped spur development; however, production in the Powder River Coal Field did not really accelerate until a new borehole completion technique (**Figure 2**) allowed companies to efficiently dewater the coal beds and release the CBNG. Further acceleration in drilling occurred after the June 1999 U.S. Supreme Court decision in *Amoco v. Southern Ute Tribe.* The Supreme Court ruled that the CBNG belonged to the oil and gas estate rather than the coal estate. The ruling took away the uncertainty of who owned the CBNG and increased the amount of CBNG controlled by private owners at the expense of federal ownership. Infrastructure improvements such as increased compression capacity, installation of numerous electrical lines to power down-hole pumps that dewater coal beds, and construction of major pipelines to transport the gas out of the Powder River Coal Field (**Figure 3**) helped cumulative production top 1.35 trillion cubic feet (TCF) through May 2004.

The area along the eastern edge of the Green River Coal Field (**Figure 4**) is potentially the next large CBNG-producing area in Wyoming. Results from a number of pilot projects have been very encouraging and development of CBNG from bituminous coal beds in the Mesaverde Group could proceed fairly rapidly. After the Environmental Impact Statement (EIS) for this area (known as the Atlantic Rim) is completed, several thousand wells could be drilled. A number of other areas in the Green River and Hanna coal fields have been explored and could become important producing areas in the future. It is also possible that CBNG may become an important commodity in the Wind River and Bighorn coal fields.

The Wyoming State Geological Survey has estimated recoverable CBNG resources for Wyoming's coal fields (**Figure 1**). These estimates are 3.3 TCF for the Green River Coal Field, 1.3 TCF for the Hanna Coal Field, 1.0 TCF for the Wind River Coal Field, 0.6 TCF for the Bighorn Coal Field, and 0.3 TCF for the Hams Fork Coal Field. Additionally, Findley and Goolsby (2000) estimated recoverable CBNG for the Powder River Coal Field. Their estimate included only coal beds greater than 20 feet thick in 3.4 million productive acres. They arrived at a gas-in-place estimate of 37 TCF; with a recovery factor of 67%, they estimated 25.2 TCF of recoverable natural gas.

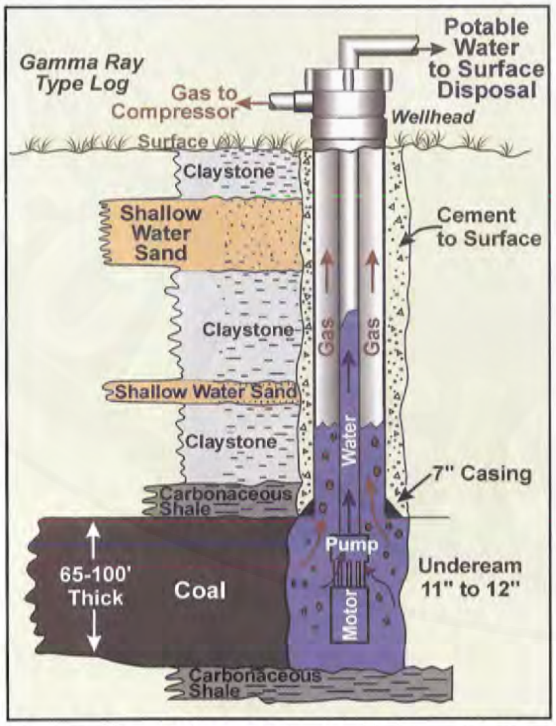

Figure 2. Schematic diagram showing open-hole completion technique for a typical coalbed natural gas well in the Powder River Coal Field. Modified from a diagram furnished by the Wyoming State Engineer's Office.

Figure 3. The 24 inch-diameter Fort Union Gas Gathering Pipeline, along with several other large pipelines, transport coalbed natural gas from the Powder River Coal Field.

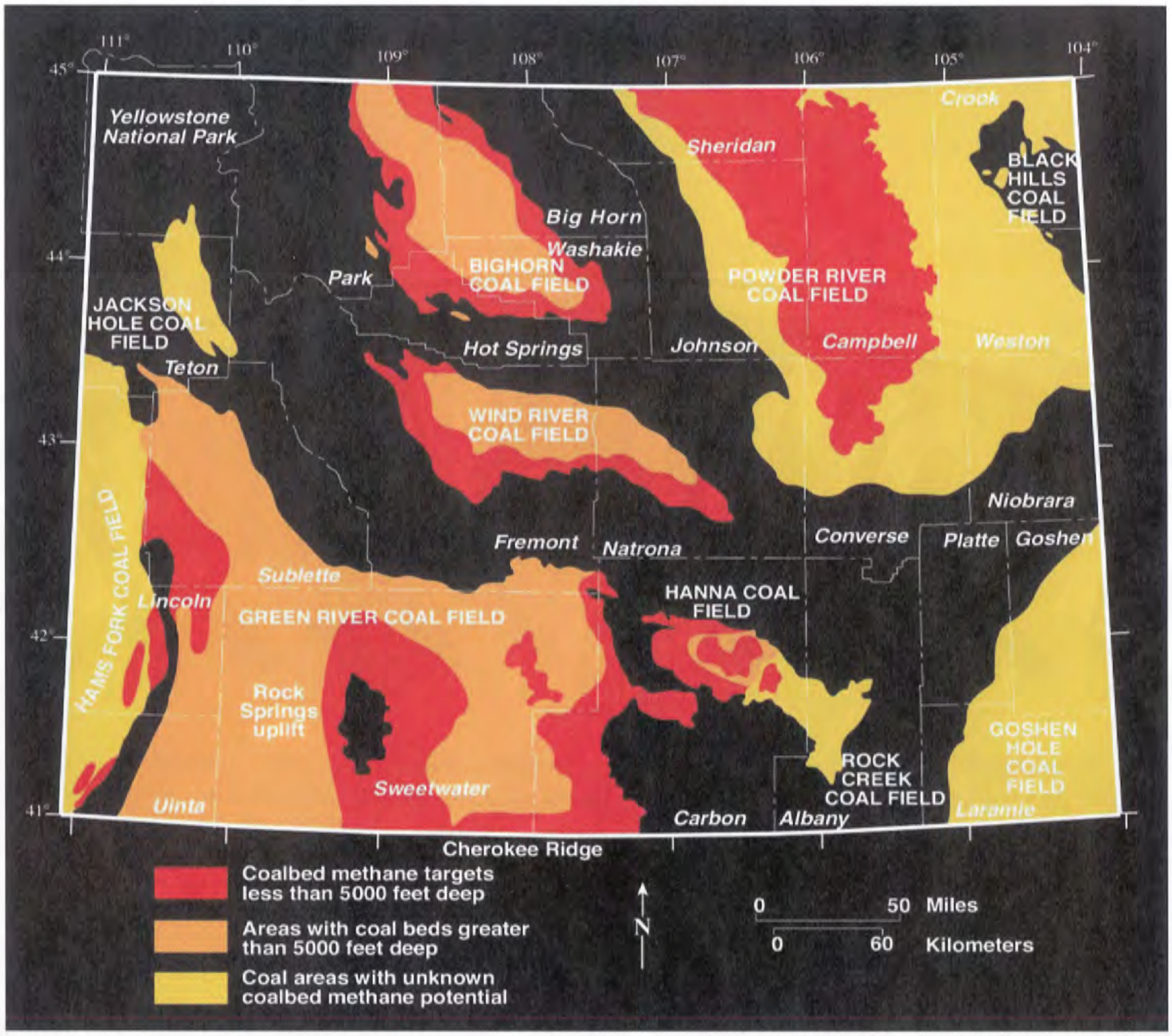

Figure 4. Exploration targets for coalbed natural gas in Wyoming. Modified from Jones and De Bruin (1990). Arrow shows the approximate location of the Atlantic Rim CBNG development.

CBNG is important to Wyoming because it now constitutes approximately 12% of Wyoming's proved reserves of natural gas (**Figure 5**). Approximately 19% of Wyoming's total natural gas production in 2003 was from coal beds (**Figure 6**). The 346 billion cubic feet (BCF) of CBNG produced from the Powder River Coal Field that year contributed about $140 million in severance taxes and royalties to the State of Wyoming; about $90 million in ad valorem taxes to Campbell, Converse, Johnson, and Sheridan counties; and about $27 million in royalties to the federal government.

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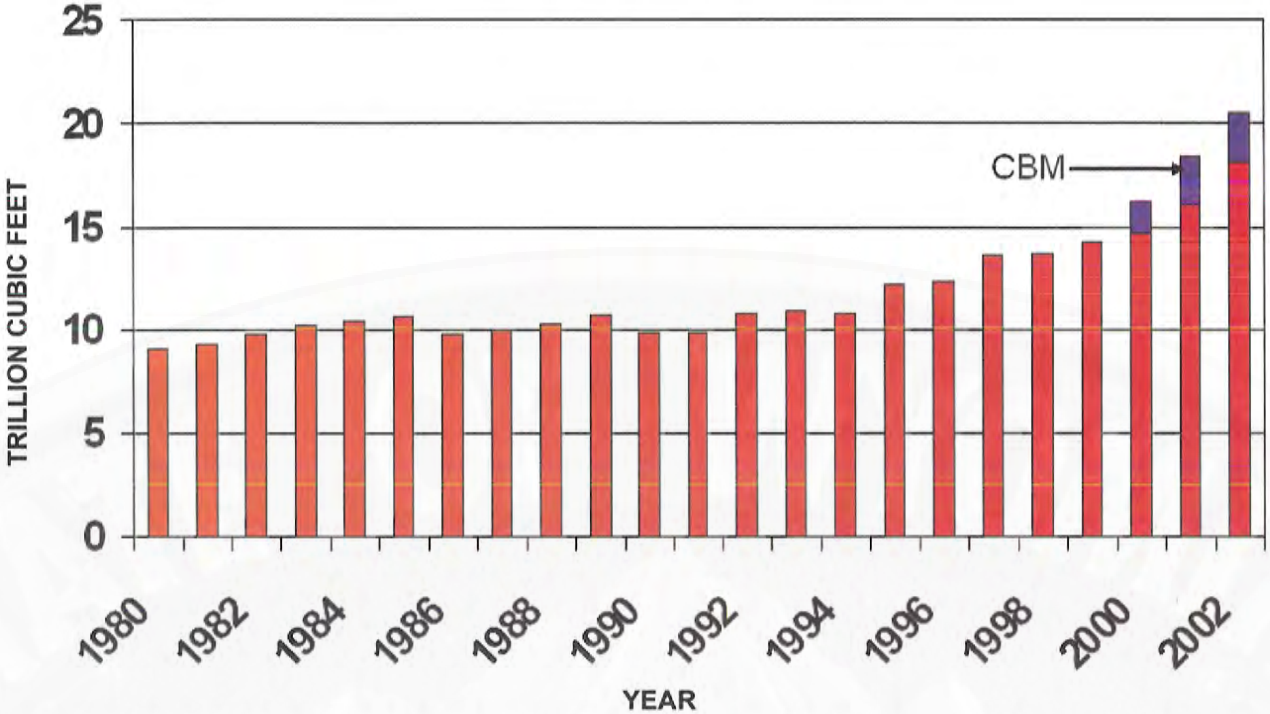

Figure 5. Wyoming's proved reserves of natural gas in trillion cubic feet (1980 through 2002) with coal-bed natural gas additions for 2000 to 2002. Modified from Energy Information Administration, 1981 to 2003.

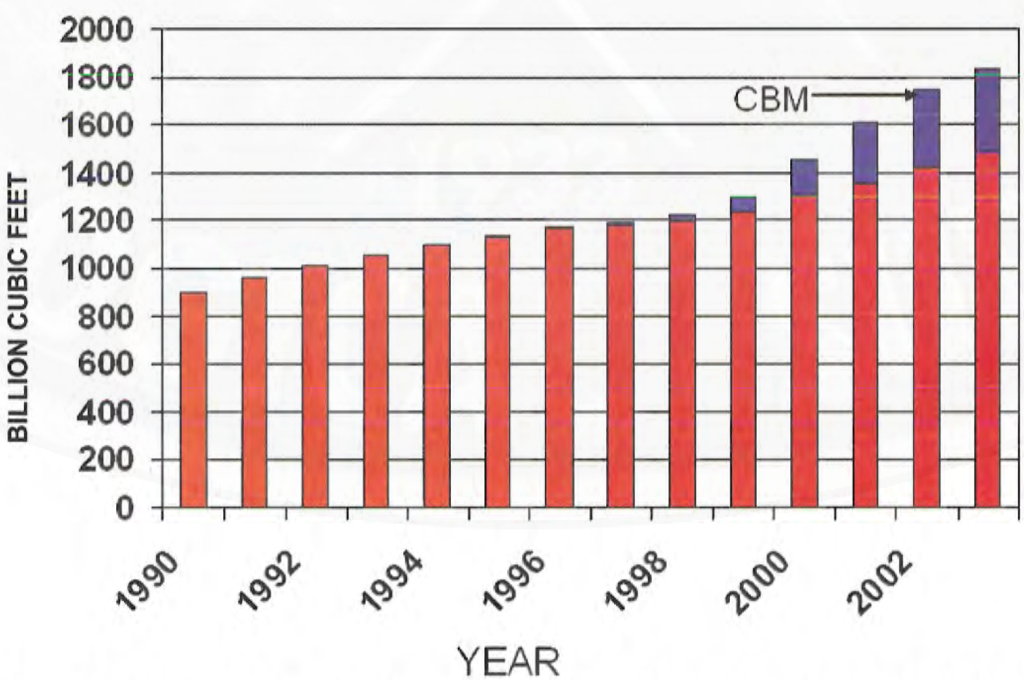

Figure 6. Wyoming's yearly natural gas production in billions of cubic feet (1990 to 2003) with the contribution made by coalbed natural gas. Source: Wyoming Oil and Gas Conservation Commission's Web site <http://wogcc.state.wy.us>.

Session 1: Surface and ground water quality and quantity
Wyoming Union, Yellowstone Ballroom
Co-Chairs: John Wagner, Wyoming Department of Environmental Quality and Carol Frost, University of Wyoming

Editor's note: Titles of presentations shown on this page may be different from the written articles published in this volume

1:00 p.m.	Geochemistry of CBM retention Pponds in the Powder River Basin–Rich Jackson, University of Wyoming; KJ Reddy, University of Wyoming; David Legg, University of Wyoming; Rich Olson, University of Wyoming
1:20 p.m.	Storm runoff and chemistry in ephemeral watersheds of the CBNG development region in NE Wyoming–Frank Sanders, CBM Associates; Buster Ivory, CBM Associates; Gretchen Kohler, CBM Associates; Hugh Lowham, Lowham Engineering; Stan Druse, Lowham Engineering
1:40 p.m.	Transport and fate of dissolved inorganic nitrogen in water discharged from coalbed methane supply wells–Richard L. Smith, U.S. Geological Survey; Deborah A. Repert, U.S. Geological Survey; Charles P. Hart, U.S. Geological Survey
2:00 p.m.	Potential effects of coalbed methane gas product waters on surface waters in the Powder River Basin, Wyoming–S.J. Clearwater, National Institute of Water and Atmospheric Research Ltd; B.A. Morris, University of Wyoming and U.S. Geological Survey; J.S. Meyer, University of Wyoming
2:20 p.m.	A Monte Carlo model of Tongue River water quality–William M. Schafer, Schafer Limited; Michael L Bergstrom, Fidelity Exploration and Production Company; William R. Thompson, Hydrometrics
2:40 p.m.	Modeling the assimilative capacity of the Powder River Basin, Wyoming–Rob Garland, CBM Associates, Inc.; Todd Gilmer, CBM Associates, Inc.; Joe Olson, Williams Production Company
3:00 p.m.	BREAK
3:30 p.m.	Preliminary results of a study of infiltration from an impoundment for coalbed methane water, Powder River Basin, Wyoming–Richard W. Healy, U.S. Geological Survey; Timothy T. Bartos, U.S. Geological Survey; Cynthia A. Rice, U.S. Geological Survey
3:50 p.m.	Preliminary results of a study of the geochemistry of the shallow alluvial aquifer in a drainage with CBM development–Karl Taboga, CBM Associates, Inc.; Rachel Toner, CBM Associates, Inc.; Frank Sanders, CBM Associates, Inc.; Buster Ivory, CBM Associates, Inc.; Gretchen Kohler, CBM Associates, Inc.
4:10 p.m.	Preliminary changes in groundwater quality related to coalbed methane infiltration ponds–John Wheaton, Montana Bureau of Mines and Geology; Andy Bobst, U.S. Bureau of Land Management; Terry Brown, Western Research Institute
4:30 p.m.	Tracking CBM infiltration pond impacts upon groundwater using strontium isotopes–Elizabeth Brinck, University of Wyoming; John Wheaton, Montana Bureau of Mines & Geology; Carol Frost, University of Wyoming

Geochemistry of coalbed methane product water across five Wyoming watersheds

R.E. Jackson, K.J. Reddy, R.A. Olson, and D.E. Legg–Department of Renewable Resources, College of Agriculture, University of Wyoming, Laramie, Wyoming

Introduction

Demand for natural gas (methane) is increasing within the United States because of the energy shortage. Further, methane is a clean form of burning fossil fuel. Several states within the U.S. (e.g., Wyoming, Colorado, Montana, New Mexico, and Utah) are exploring methane extraction from their coal resources. As an example, in the Powder River Basin (PRB) of Wyoming, it is estimated that there are 31.7 trillion cubic feet of recoverable coalbed methane (CBM). Currently, CBM development in this basin is occurring rapidly as demand for natural gas has increased in the U.S. (De Bruin and others, 2000).

Recovery of the methane is facilitated by pumping water from the aquifer (product water). It is estimated that a single CBM well in the PRB may produce from 8 to 80 liters (L) of product water per minute; this amount varies with the aquifer that is being pumped and the density of the wells. At present, more than 16,000 wells are under production in the PRB and this number is expected to increase to at least 30,000. Based on information provided by the Wyoming State Geological Survey, approximately 2 trillion L of product water will eventually be produced from CBM extraction in Wyoming. Commonly 2 to 10 CBM extraction wells are placed together in a manifold system discharging to a single point and releasing into constructed unlined disposal ponds.

Little information is available on the geochemistry of CBM product water and associated disposal ponds in the PRB (Rice and others, 1999; McBeth and others, 2003a and b). Studies conducted by Rice and others (1999) only examined the chemistry of CBM discharge water at the wellhead. McBeth and others (2003a and b) examined the chemistry changes of product water both at wellhead and in disposal ponds of the RPB. However, to our knowledge no studies involved monitoring the geochemical processes that product water undergoes in disposal ponds across the Powder River Basin. The CBM product water discharged to the surface is managed and regulated by several state and federal agencies. To effectively manage this water resource there is a need to understand the geochemical changes that occur in CBM disposal ponds over time.

Objectives

The overall objectives of this research are to: (1) collect product water samples from discharge points and disposal ponds over a period of three years and analyze for pH, DO, EC, major cations (e.g., Ca, Mg, Na, and K), major anions (e.g., alkalinity, sulfate, chloride, fluoride, nitrate, and phosphate), and trace elements (e.g., Al, As, Ba, B, Fe, Cd, Cu, Cr, Mn, Mo, Se, Pb, and Zn); (2) monitor the pH, DO, EC, major cations (e.g., Ca, Mg, Na, and K), major anions (e.g., alkalinity, sulfate, chloride, fluoride, nitrate, and phosphate), and trace elements (e.g., Al, As, Ba, B, Fe, Cd, Cu, Cr, Mn, Mo, Se, Pb, and Zn) of product water at discharge points and associated ponds over a period of 3 years; (3) predict geochemical changes (speciation, adsorption, and precipitation) for critical metals such as Fe, Ba, As, and Se in the disposal pond; and (4) Quantify relationships between CBM water quality, aquatic macroinvertebrates, and vegetation.

We selected twenty-four sites within five Wyoming watersheds to obtain CBM well and associated pond data (**Figure 1**). We sampled seven sites in each of the Little Powder River (LPR) and Powder River (PR) watersheds. We sampled three sites from Cheyenne River (CHR) watershed, three sites from Belle Fourche River

(BFR) watershed, and four sites from Tongue River (TR) watershed (**Figure 1**). Before samples were collected, field measurements including pH, conductivity, temperature, ORP, and dissolved oxygen were taken in each well and pond. Duplicate water samples of wells and ponds were taken from each site as well as three trip blanks (112 total water samples).

Water samples were analyzed for: Ca, Na, Mg, K, Fe, Al, Cr, Mn, Pb, Cu, Zn, As, Se, Mo, Cd, Ba, and B by ICP-MS. Sulfate, chloride, fluoride, nitrate, and phosphorus were analyzed on IC. In addition to these analyses, samples were analyzed for dissolved organic carbon due to appearance of organic matter in disposal ponds. All analyses were performed following CFR 40, Part 1, Chapter 36 procedures (Wyoming DEQ, 2001). Sites used to sample pond sediment were located directly away from discharge and locations were chosen upon pH stabilization at different distances from discharge point. Typically, sediment was collected approximately three meters into pond from discharge point. Sediment was taken from every pond. At least two samples from each watershed (10 total samples) will be separated into different mineral fractions and each fraction will be dissolved in an appropriate solution and extracted. Each clear extract will be analyzed for Fe, Ba, As, and Se on ICP-MS as described by Tessier and others (1979).

Macroinvertebrates were collected from the water column and sediment from two ponds in each different watershed (20 total samples). Identification to lowest taxonomic level will be conducted using a certified laboratory specializing in analysis of benthic invertebrate communities. A vegetation species list of all vegetation that was present in and around ponds was conducted for every pond. Paired T-tests were used to identify differences between discharge wells and their associated ponds (**Table 1**). One-way ANOVAs were used on individual CBM discharge wells and pond water to identify differences between watersheds, and if there were differences, Tukey mean separation test was used to further identify these differences.

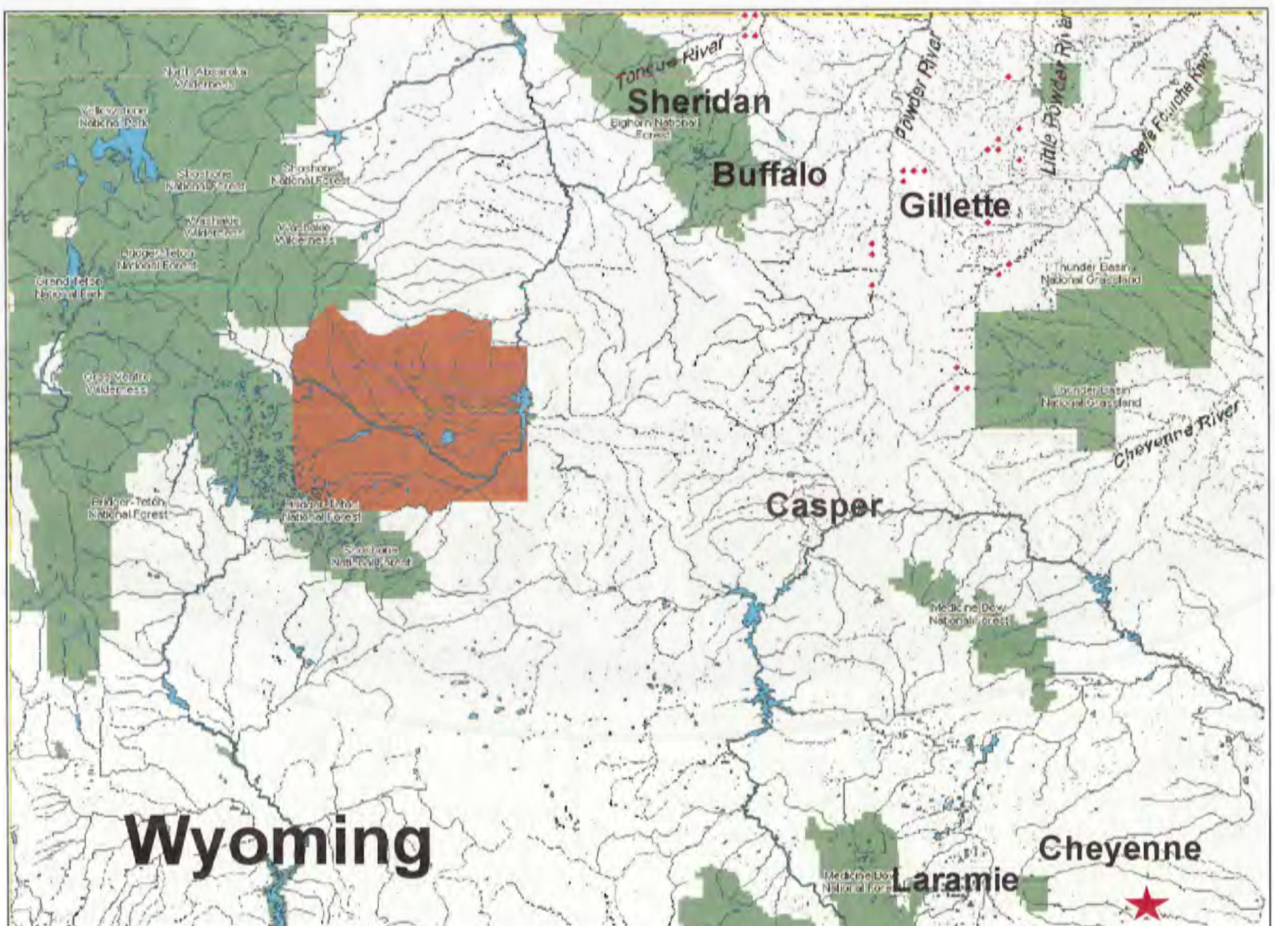

Figure 1. Study site locations by watershed.

Table 1. Significant differences from paired t-tests comparing discharge well versus associated discharge ponds.

pH			
Watershed	N	T-value	P-value
BFR	3	2.43	0.136
CHR	3	2.79	0.108
LPR*	7	4.56	0.004
PR*	6	3.92	0.011
TR*	4	14.41	0.001
Alkalinity			
Watershed	N	T-value	P-value
BFR	3	-3.52	0.072
CHR	3	-0.99	0.427
LPR	7	0.76	0.476
PR	6	0.15	0.889
TR*	4	3.85	0.031
Manganese			
Watershed	N	T-value	P-value
BFR	3	-1.02	0.413
CHR	3	-1.90	0.197
LPR	7	-1.03	0.342
PR	6	0.37	0.727
TR*	4	-7.49	0.005
Sodium			
Watershed	N	T-value	P-value
BFR	3	0.34	0.765
CHR	3	0.28	0.803
LPR	7	0.69	0.516
PR	6	0.13	0.904
TR*	4	3.13	0.046
Barium			
Watershed	N	T-value	P-value
BFR	3	-1.17	0.363
CHR	3	-2.36	0.142
LPR*	7	-3.52	0.012
PR*	6	-2.80	0.038
TR*	4	-6.69	0.007

*** Indicates statistical difference at 0.05 alpha level.**

Results

Measured parameters that were statistically different in discharge wells were usually different in discharge ponds. Discharge well pH was statistically different between watersheds while pond pH was not significantly different. Alkalinity, EC, Na concentrations, and B concentrations for both discharge wells and ponds increased when heading northwest from CHR to PR and then decreased at TR. The pH of CBM water increased from discharge wells to associated ponds in all watersheds. Arsenic and Copper concentrations appeared to increase from discharge wells to ponds, while Barium concentrations decreased. The practical sodium adsorption ratio (SAR) increased in both discharge wells and disposal ponds from Cheyenne River Watershed to Tongue River Watershed with an observed SAR approaching 35 in Tongue River Watershed.

Future studies

Future plans and experiments include: two more years of data collection and sediment fractionation experiments to identify exchangeable, carbonate bound, Fe/Mn oxide bound, organic matter bound, and residual fractions of Ba, Fe, As, and Se, and aquatic macroinvertebrate identification. I will begin more statistical analysis to identify trends in anion/cation accumulation in discharge ponds, and create a model to predict SAR of ponds from associated discharge wells.

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Storm runoff and chemistry in ephemeral watersheds of the CBNG development region in northeastern Wyoming

Frank Sanders, Buster Ivory, and Gretchen Kohler–CBM Associates, Inc., Laramie, Wyoming
Hugh Lowham and Stan Druse–Lowham Engineering, Gillette, Wyoming

Management of coalbed natural gas (CBNG) produced water commonly results in the discharge of significant water volumes to semi-arid ephemeral drainages typical of the northeast Wyoming gas development region (**Figure 1**). Because data on the baseline chemistry of infrequent surface flows in these ephemeral drainages is sparse, the potential effects of these discharges on the chemistry of surface drainage have been studied since 2001 in a series of representative watersheds in both CBNG developed and non-developed areas. Monitoring is being conducted at the outlets of the study watersheds. Thus, watershed-level processes are being monitored on a relatively large spatial scale.

Many of the study watersheds are instrumented with Continuous Record Stations (CRS) that continuously monitor the hydrograph (generally 5 to 15 minute intervals) and contain an automatic water sampling device which takes 24 discrete water samples at preprogrammed time intervals during storm flow. The CRS water samples are analyzed for dominant cation and anion chemistry. Other watersheds are instrumented with Partial Record Stations (PRS) that continuously monitor the hydrograph and specific conductance. This presentation provides an overview of major observations primarily during the 2001 and 2002 water years. Additional data collected during the 2003 and the 2004 water years are currently being evaluated (**Table 1**).

Several storm flows were observed in the study watersheds during late summer 2002. Storm hydrographs and general storm discharge chemistry (**Figures 2** through **5**) are consistent with results of other regional studies conducted by the USGS prior to CBNG development. Results demonstrate that site-specific catchment and individual storm characteristics produce variable hydrologic and geochemical conditions during runoff events in ephemeral watersheds in NE Wyoming. Site-specific conditions for individual watershed/storm combinations are important determinants for yield (export) of specific solute per unit watershed area, yield of total salts per unit area, and flow-weighted discharge chemistry.

In general, three sequential phases to storm flow hydrographs and associated chemistry were commonly observed (**Figures 6** and **7**). These can be generally described as a brief initial flow at the monitoring gage characterized by relatively low specific conductance that apparently reflects nearby sheet overland runoff with little soil/water interaction; a short-duration, leading edge of the main storm surge characterized by high salt washout derived from upstream potholes and dissolution/transport of salts (evaporites) present along the stream channel and in surficial soils on hillsides during initial inundation; and a relatively long-duration descending limb of the hydrograph characterized by substantial discharge and by relatively high quality water in comparison to the peak discharge.

The high salt contents observed in the study watersheds during the initial peak discharge periods of the storm hydrographs are consistent with the results of studies conducted in ephemeral streams in other semiarid regions of Wyoming by the USGS prior to CBNG development. Thus, the presence of a salt plume at the leading edge of storm discharge from an ephemeral drainage in NE Wyoming is a natural occurrence and is not necessarily related to CBNG development.

Total yields per unit area of dissolved salts from developed watersheds observed to date have wide variability dependent upon study location and individual

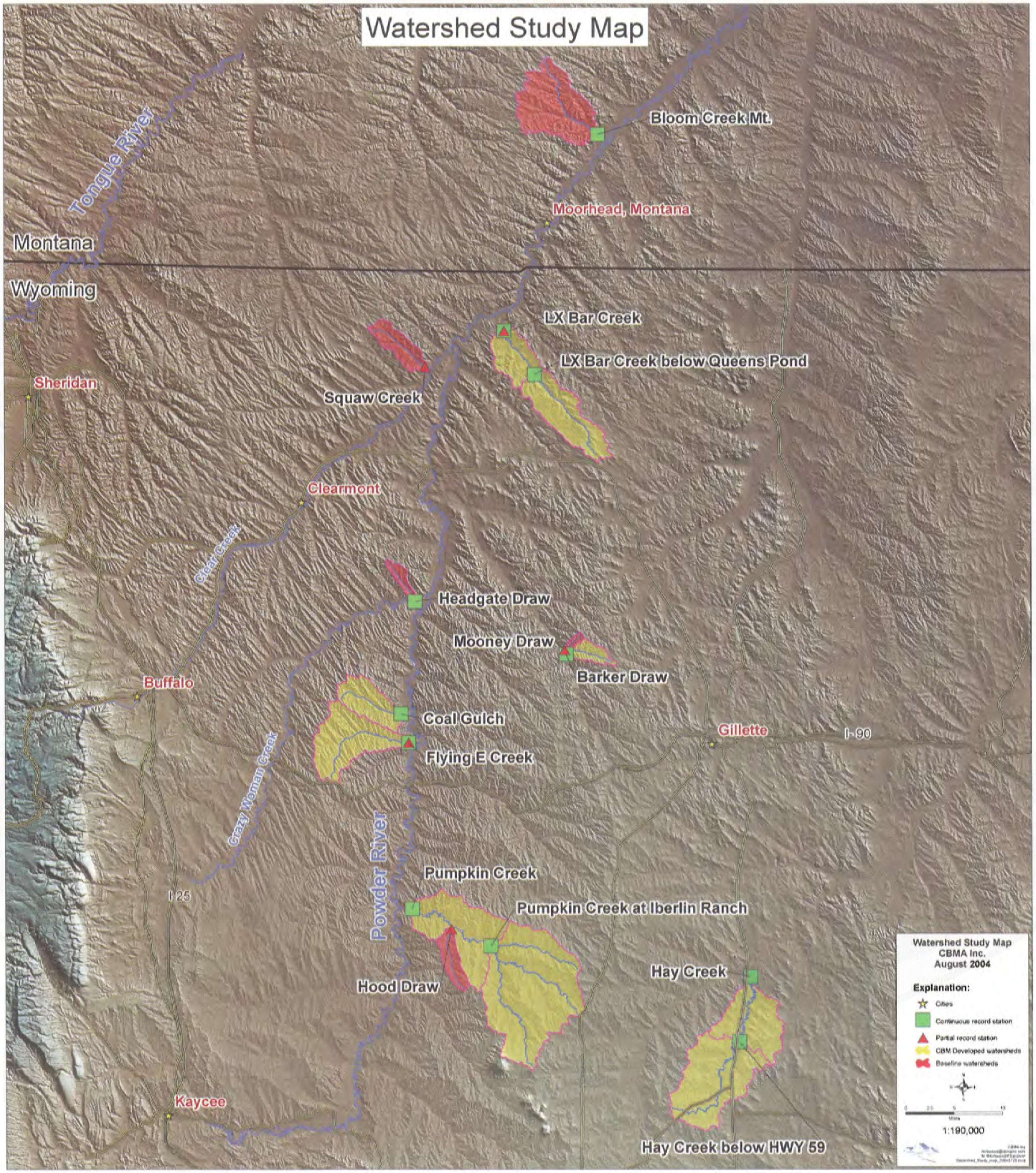

Figure 1. Map showing locations of watersheds that were monitored during this study.

Table 1. Study drainage summary for 2004.							
Stream	Tributary to	Hydrology	Drainage area above station (sq. miles)	Stream length above station (miles)	Percent stream slope (%)	Predominant Exposed Geology	Monitoring start date
Continuous Record Stations:							
Barker Draw near Mouth	Wild Horse Creek, tributary of Powder River	Ephemeral	7.41	6.8	16.42	Tertiary: Wasatch Formation	May, 2001
Pumpkin Creek near Mouth	Powder River	Ephemeral	165.63	39.74	7.62	Tertiary: Wasatch Formation	May, 2001
Pumpkin Creek at Iberlin Ranch	Powder River	Ephemeral	106.76	21.49 (along South Prong)	6.27	Tertiary: Wasatch Formation	May, 2001
Hay Creek near Mouth	Belle Fourche River	Perennial	95.8	40.95	5.34	Tertiary: Wasatch Formation	October, 2001
Hay Creek at Hwy 59	Belle Fourche River	Perennial	58.7	22.24	5.42	Tertiary: Wasatch Formation	September, 2001
LX Bar Creek near mouth	Powder River	Ephemeral	56.64	25.8	9.81	Tertiary: Fort Union Formation	March, 2003
LX Bar Creek below Queens Pond	Powder River	Ephemeral	36.25	15.13	8.35	Tertiary: Fort Union Formation	July, 2003
Bloom Creek near mouth; Montana	Powder River	Ephemeral	46.9	16.8	17.82	Tertiary: Fort Union Formation	August, 2003
Flying E Creek near mouth	Powder River	Ephemeral	41.35	16.91	14.46	Tertiary: Wasatch Formation	May, 2003
Coal Gulch near mouth	Powder River	Ephemeral	21.74	9.24	17.29	Tertiary: Wasatch Formation	June, 2003
Partial Record Stations:							
Mooney Draw	Wildhorse Creek, tributary of Powder River	Ephemeral	1.8	3.4	21.45	Tertiary: Wasatch Formation	August, 2001
Hood Draw	Pumpkin Creek, tributary of Powder River	Ephemeral	10.4	8.47	9.76	Tertiary: Wasatch Formation	May, 2002
Headgate Draw	Crazy Woman Creek, tributary of Powder River	Ephemeral	4.5	6.4	15.96	Tertiary: Wasatch Formation	May, 2002
Squaw Creek near mouth	Clear Creek, tributary of Powder River	Ephemeral	13.59	10	13.44	Tertiary: Fort Union Formation	May, 2003
LX Bar Creek near mouth	Powder River	Ephemeral	56.64	25.8	9.81	Tertiary: Fort Union Formation	March, 2003
Flying E Creek near mouth	Powder River	Ephemeral	41.35	16.9	14.46	Tertiary: Wasatch Formation	June, 2004

storm. Salt concentrations during storm flow from non-developed watersheds overlap those observed for developed drainages. The wide range of observed storm types and chemistry suggests that a considerable number of storm events will need to be monitored to allow adequate statistical comparison between developed and non-developed drainages regarding salt export during storm flows.

Observed storm discharge chemistry is consistent with natural geological materials being the source of exported salts. The following lines of evidence support this finding:

- Mole ratios of dominant cations and anions are consistent with the dissolution and transport of native salts (evaporites) and the flushing of related pot hole waters during storm flow;
- High r-squared correlations (**Table 2**) between sodium:calcium and sodium:sulfate ion pairs (moles/l) suggest that CBNG-derived sodium, if entrained during storm flows, is being swamped by sodium flux originating from natural landscape materials because neither calcium nor sulfate occurs to any appreciable degree in CBNG produced water.

Table 2. R-squared correlations between paired variables (concentrations in mg/L) for storm flows monitored during the 2002 water year.

Storm Flow Event	Na:SO4	Ca:SO4	Na:Ca
Barker Draw: Aug. 21-22	0.656	0.838	0.413
Barker Draw: Aug. 27-28	0.904	0.987	0.871
Pumpkin Crk at Iberlin Ranch	0.99	0.981	0.985
Pumpkin Crk near Mouth: Aug. 21-22	0.956	0.094	0.165
Pumpkin Crk near Mouth: Aug. 28-31	0.917	0.603	0.33
Hay Creek at Mouth: June 1-6	0.987	0.97	0.983

- The specific conductance of storm flows in non-developed drainages overlay considerably with the specific conductance observed during storm discharges in developed watersheds.

Although the chemical signature of CBNG discharges is not evident in storm flows observed in the study watersheds, results to date are not sufficient to allow a quantitative assessment of CBNG-related effects on salt yield. Further quantitative study is required to substantiate these initial findings. The monitoring program is ongoing and several more years of storm flow data are expected to be collected from the study watersheds.

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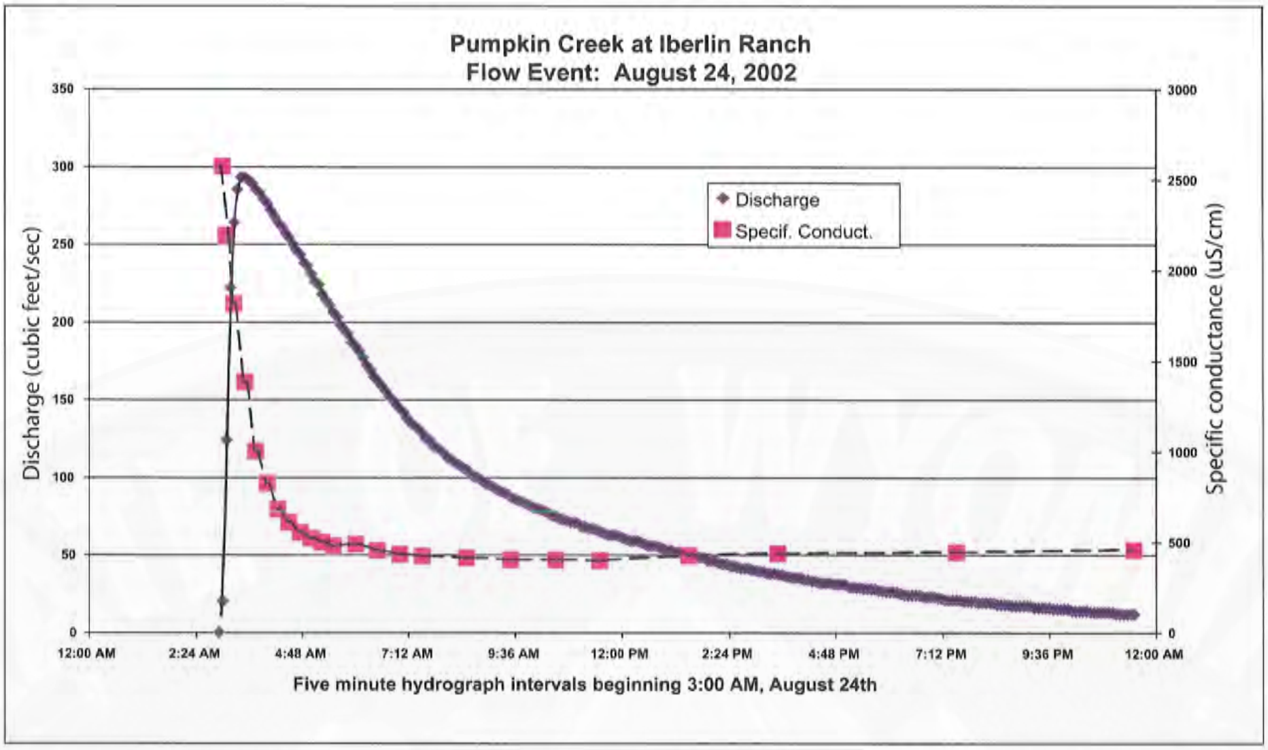

Figure 2. Discharge rate in cubic feet per second and specific conductance for the August 24, 2002 Pumpkin Creek flow event at Iberlin Ranch.

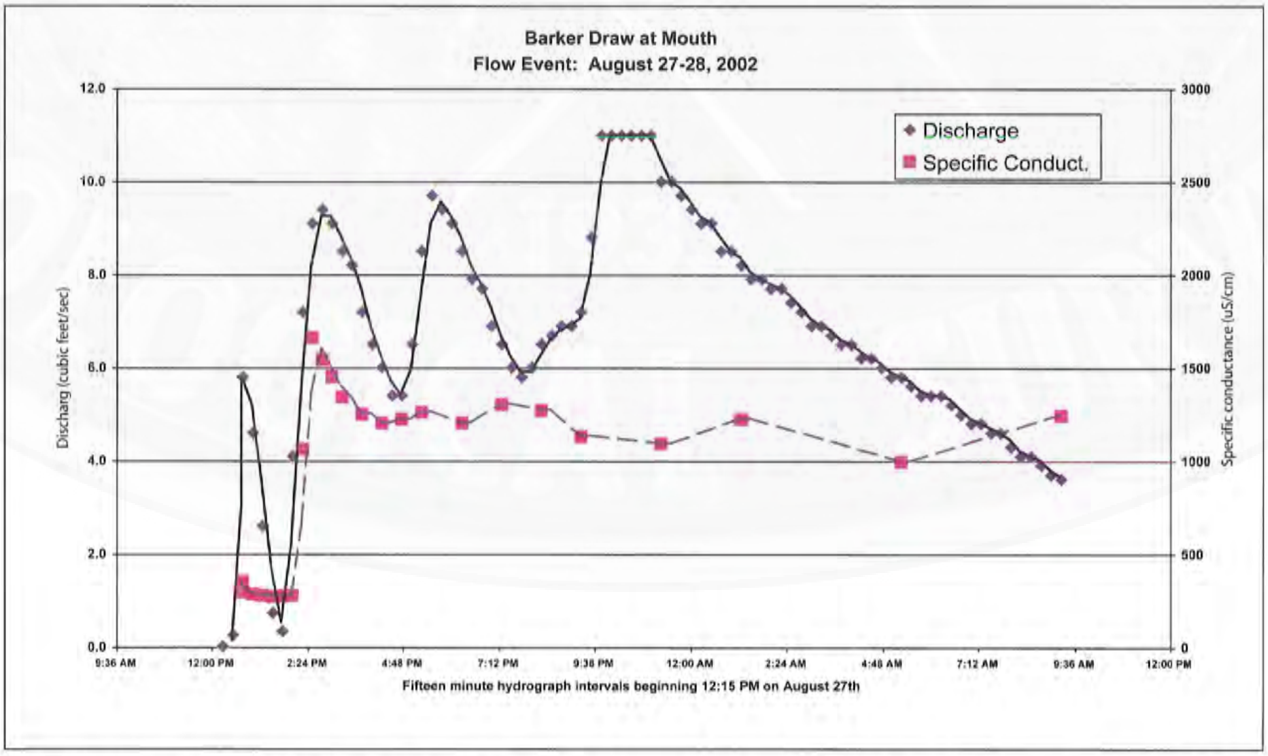

Figure 3. Discharge rate in cubic feet per second and specific conductance for the August 27-28, 2002 Barker Draw flow event at Mouth.

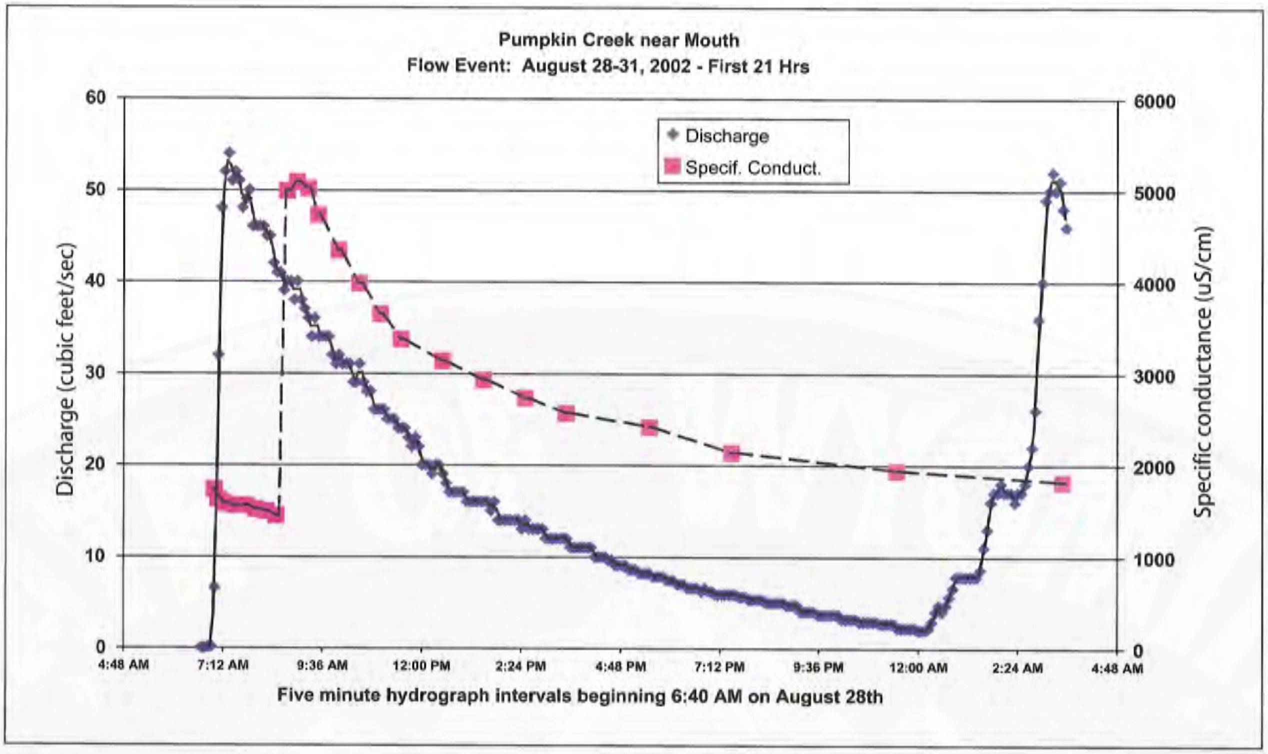

Figure 4. Discharge rate in cubic feet per second and specific conductance for the August 28-31, 2002 Pumpkin Creek flow event near mouth.

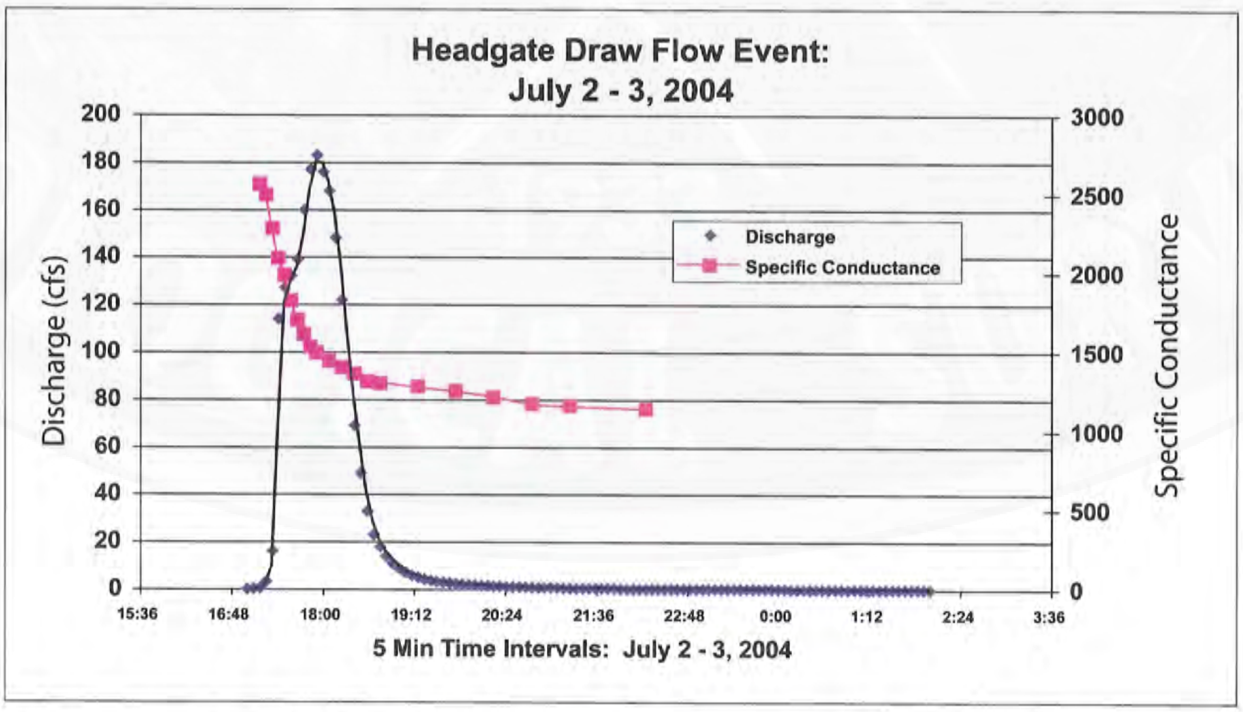

Figure 5. Discharge rate in cubic feet per second and specific conductance for the July 2-3, 2004 Headgate Draw flow event.

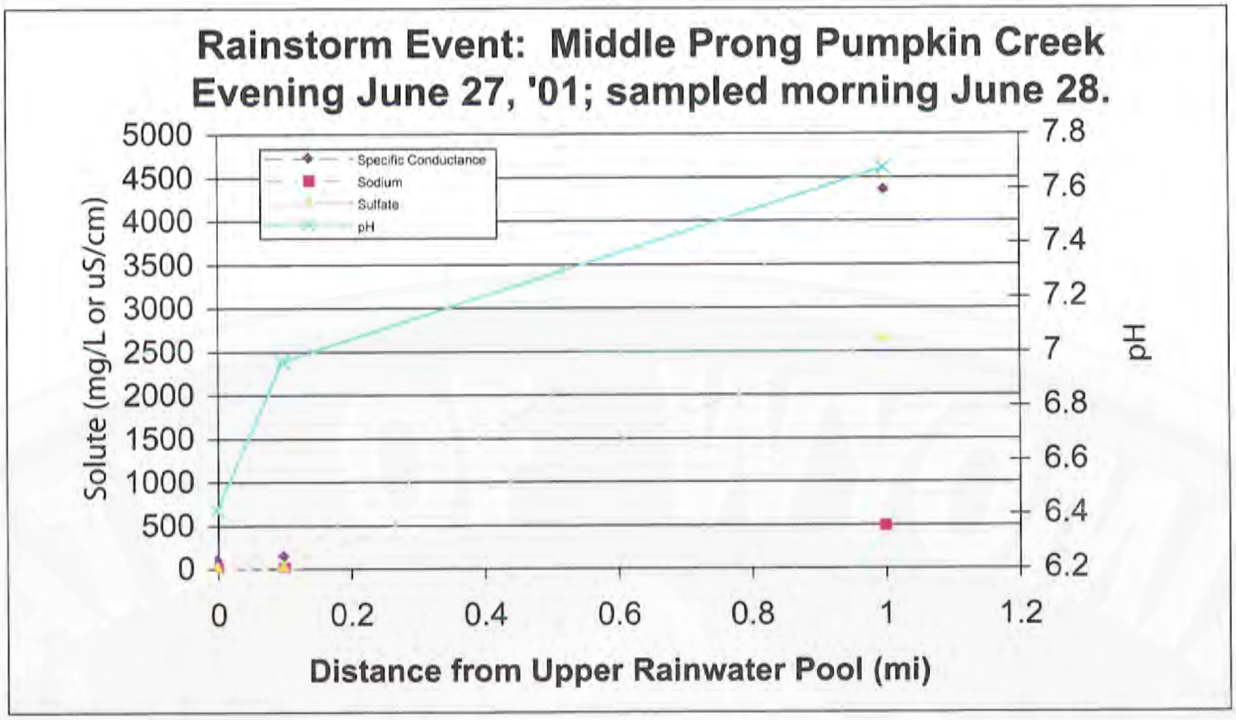

Figure 6. Specific conductance, sodium, sulfate, and pH levels for the June 27, 2001 Middle Prong Pumpkin Creek event.

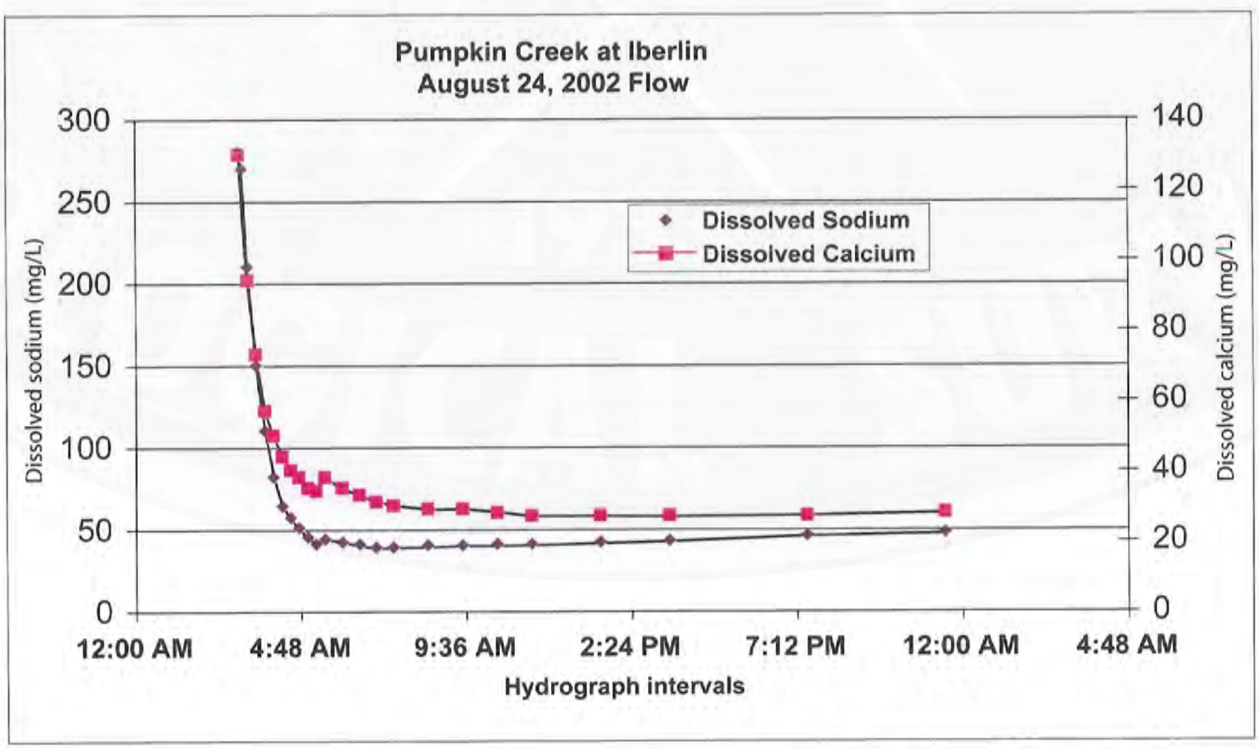

Figure 7. Dissolved sodium and calcium levels in mg/L for August 24, 2002 Pumpkin Creek flow at Iberlin.

Transport and fate of dissolved inorganic nitrogen in water discharged from coalbed methane supply wells, Powder River Basin, Wyoming

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Water originating from coalbed methane (CBM) production wells typically contains reduced chemical constituents, including ammonium, and is often disposed via discharge to stream channels and reservoirs. At present, little is known about the effect of biogeochemical and hydrologic processes on the downstream composition of these waters subsequent to discharge, particularly with respect to redox-sensitive constituents. A field study was conducted in a Powder River tributary to document changes in CBM water composition, with particular emphasis on nitrogen-cycling processes and the fate of ammonium. Ammonium concentrations in a variety of CBM discharge waters ranged from 1.3-8.0 mg N/L. Within specific channels, ammonium concentrations decreased with transport distance via nitrification, with subsequent increases in nitrite and nitrate. In some cases, nitrite concentrations significantly exceeded the drinking water limit of 1 mg N/L.

Removal of total dissolved inorganic nitrogen (DIN) was efficient in a small, single discharge channel (discharge of 0.17 m^3/min), with complete oxidation of ammonium to nitrate after 0.5 km travel distance. DIN removal efficiency was highly correlated with diel patterns of incident light and dissolved oxygen concentration, ranging from 82-49% mid-night to noon. In a larger channel (discharge of 2.9 m^3/min) with multiple inputs, DIN concentrations were >4.2 mg N/L after 5 km of transport. Ammonium represented 25-30% of the large channel DIN and remained relatively constant with time, with only a weak diel pattern evident. In July 2003, the daily large channel DIN load average was 23 kg N/day entering the Powder River. The results of this study suggest that CBM discharge can serve as a significant source of dissolved nitrogen to western watersheds and that net oxidation and/or removal is dependent upon the extent of contact with sediment and biomass, time of day, and perhaps adaptation time of the plant and microbial in-stream communities.

Potential effects of coalbed natural gas product waters on surface waters in the Powder River Basin, Wyoming

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Large volumes of coalbed natural gas (CBNG) are being extracted from the Powder River Basin (PRB) in Wyoming. To extract CBNG, groundwater is pumped to the surface and either discharged, stored in holding ponds, or re-injected. There are concerns that discharged groundwater (i.e., CBNG product water) will negatively impact surface waters by altering the hydrology, salinity, and temperature of receiving waters, thus altering aquatic communities. In this study, we surveyed historic data on surface water quality in the PRB (National Water Information System; http://water.usgs.gov/nwis) and compared it to the quality of CBNG product waters [Rice and others (2000), Forbes and others (2001), Petroleum Association of Wyoming (2001), and National Pollutant Discharge Elimination System (NPDES) permits filed with the Wyoming Department of Environmental Quality (WDEQ) through May 2001]. We also examined literature about the toxicity of major ions to aquatic organisms (especially Mount and others, 1997). Additional details of the study design and results appear in Clearwater and others (2002).

Surface water quality, especially salinity and major ion composition, differs considerably across the PRB, as does the quality of CBNG product water. In particular, the Powder River is much more turbid and saline than the Tongue River. Also, the ionic compositions of the saline waters of the Powder River differ significantly from those of the Belle Fourche River and the Little Powder River. In contrast, electrical conductivity, total dissolved solids, and alkalinity of CBNG product waters tend to increase from wells southeast of the Belle Fourche River to wells near the Powder River, east of the junction with Clear Creek. Therefore, CBNG product water quality will have different impacts on each of the major waterways of the PRB. In some drainages, CBNG product water will tend to "salinate" receiving waters; whereas in other drainages, CBNG product water will tend to "dilute" receiving waters. We recommend that the tendency for CBNG product waters to "dilute" some surface waters be considered just as potentially important to resident biota as is the tendency for CBNG product waters to "salinate" other surface waters.

Product water from CBNG wells located east of the Powder River will tend to (1) increase sodium (Na^+) and bicarbonate (HCO_3^-) concentrations in much of the Powder River and (2) decrease chloride (Cl^-) and sulfate (SO_4^{2-}) concentrations and the water hardness (an index of the sum of the calcium (Ca^{2+}) and magnesium (Mg^{2+}) concentrations). Limited information about CBNG wells near the Tongue River suggests that product water might increase the salinity of the Tongue River. Because the Tongue River (to at least the Montana border), Piney Creek, Clear Creek (to several km downstream from Piney Creek), Crazy Woman Creek (to approximately I-25), the North Fork of the Powder River, and the Middle Fork of the Powder River (to approximately I-25) provide relatively high-quality, low-salinity habitat for salmonid fishes, major increases in salinity and changes in ion ratios in those surface waters due to discharge of CBNG product water might have significant impacts on recreational fisheries.

Limited data about CBNG product water from wells located around the Little Powder River suggest that product water is more dilute than the surface waters, except with regard to alkalinity. Therefore, CBNG product waters will tend to decrease Ca^{2+}, Mg^{2+}, and SO_4^{2-} concentrations in the Little Powder River, but increase HCO_3^- concentrations. Product waters from CBNG wells located around the Belle Fourche River tend to be more dilute than surface waters, except with regard to alkalinity (mostly HCO_3^- at those pH values), Na^+, Cl^- and potassium (K^+) concentrations. More data are required to conduct a more thorough and updated assessment of CBNG product water quality, particularly from wells around Piney Creek and Clear Creek, the North and South Forks of the Powder River, Salt Creek, and the Tongue River.

In addition to alterations of surface-water chemistry that might be caused by CBNG product waters, the environmental cues of seasonal cycles in water quality (especially temperature and turbidity) and flow rate of surface waters in the PRB will be dampened by constant inflows of relatively constant-temperature CBNG product water. All of these trends probably will have important consequences to the unique biota that thrive in unpredictable turbid, saline environments. Additionally, analysis of surface water and CBNG product-water quality relative to lethality data for three commonly used aquatic toxicity testing species (*Daphnia magna*, *Ceriodaphnia dubia* and *Pimephales promelas*) indicates that at some times and in some locations, either surface waters or undiluted CBNG product waters can be acutely lethal to some aquatic organisms. When surface waters are toxic to standard toxicity testing species, a different approach is needed to assess the impact of CBNG on resident biota.

Current regulatory practice allows water quality of wells ≤20 miles (i.e., ≤32 km) away to be used as a surrogate for the water quality of proposed CBNG wells in NPDES permit applications, if the wells are located at the same depth and within the same geological formation. However, our results indicate that CBNG product water quality can vary considerably among CBNG wells, and well depth and geological formation are not strongly related to CBNG product water quality. If WDEQ continues to allow CBNG operators to use water samples from wells ≤20 miles away to provide surrogate water quality for NPDES discharge permits (even if the wells are drilled to the same depth and within the same geological formation), we recommend that follow-up chemical analyses of the water quality be submitted to WDEQ after the well is drilled -- to verify the appropriateness of that surrogate water quality data.

Acknowledgements

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A Monte Carlo model of Tongue River water quality

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Abstract

The State of Montana recently promulgated numeric standards for electrical conductivity (EC) and sodium adsorption ratio (SAR) in the Tongue River and other streams in southeastern Montana. Previously, protection of irrigation water was provided through a narrative standard, a practice commonly used in most western states. The numeric standards that apply to selected stream reaches in southwestern Montana were adopted to protect irrigation water quality, the primary consumptive use of surface water in the drainages. One provision of the standards is a requirement for surface water discharge permits to be "flow-based." In a flow-based approach, the permitted discharge rate for groundwater produced by coalbed natural gas (CBNG) operations is adjusted as ambient stream flow varies.

The authors developed a spreadsheet-based, dynamic mass load model of the Tongue River to use as a tool for evaluating the potential effects of CBNG discharges. The model was calibrated using historic flow rates and water quality of the Tongue River and of produced water. Additionally, the model was used to estimate the assimilative capacity of the Tongue River to receive CBNG water at various in-stream flows. The model employs a Monte Carlo technique to simulate variability in future stream flows, produced water, and water quality, and to evaluate future downstream compliance with water quality standards.

Introduction

Fidelity Exploration & Production Company (Fidelity) produces coalbed natural gas (CBNG) in the CX Field, located in the Tongue River basin of Montana. Typical CBNG wells are completed in one of three coal seams ranging from 400 to 800 feet deep and produce 5 to 10 gallons per minute (gpm) of groundwater from the coal. Pumping water from the coal reduces hydrostatic pressure, which causes gas phase release of sorbed methane trapped in the coal. Since 1999, a portion (up to 1600 gpm) of Fidelity's produced water has been managed by direct discharge to the Tongue River. Discharge is permitted by the Montana Department of Environmental Quality (MDEQ) under their National Pollutant Discharge Elimination System (NPDES) permit program.

The primary beneficial use of surface water in the Tongue River is irrigation of alfalfa and grass hay, and various field and row crops. Many irrigators and environmental groups oppose CBNG development because of concerns about potential impacts to water quality from the produced groundwater. Water contained in coal seams in most of the Tongue River basin contains moderate levels of dissolved solids, dominated by sodium and bicarbonate ions (**Table 1**).

In response to irrigation water quality concerns, the State of Montana promulgated numeric standards (**Table 2**) in 2003 for electrical conductivity (EC) and sodium adsorption ratio (SAR). Previously, the MDEQ,

Table 1. Average chemical composition of produced groundwater from the Tongue River basin coal aquifers.

Constituent	n	Mean	Standard Deviation
Lab EC (µS/cm)	408	1970	193
pH (SU)	416	7.85	0.28
Ammonia (mg/L)	408	1.78	0.35
Calcium (mg/L)	415	4.94	4.59
Magnesium (mg/L)	415	1.93	7.06
Sodium (mg/L)	415	501	56

Table 2. Numeric water quality standards for EC and SAR in the Tongue River.

Reach/Season	Electrical Conductivity (µS/cm)		Sodium Adsorption Ratio	
	Monthly average	Instantaneous Maximum	Monthly average	Instantaneous Maximum
March through October (irrigation season)				
Tongue River Reservoir	1000	1500	3.0	4.5
Tongue River Mainstem	1000	1500	3.0	4.5
November through February (non irrigation season)				
Tongue River Reservoir	1000	1500	3.0	4.5
Tongue River Mainstem	1500	2500	5.0	7.5

like most other western states, used a narrative standard for protection of irrigation water quality. Numeric standards were only adopted for specific stream segments in southeastern Montana where CBNG development is expected to occur. Numeric limits differ for the Powder River, Tongue River, and Rosebud Creek drainages, and for tributaries. An important aspect of the numeric standards is that "flow-based" permits are required. [MCA §17.30.670 7) For purposes of determining compliance with the water quality standards and non-significance criteria for all parameters of concern in any new or increased discharge of unaltered ground water from coal bed methane development, the department shall determine effluent or compliance limits (e.g., evaluate the design of disposal systems) by using a **flow-based** analysis that considers a range of flows or monthly flow probability. With respect to EC and SAR, the department shall also use the median chemistry for the specified flow range or monthly flow.]

The technical approach commonly used for developing NPDES permit effluent limits (EPA, 1991) is based on protecting water quality during critical low periods such as a 7-day, 10-year or 1-day, 3-year low flow. In order to develop flow-based permit limits, the authors developed a spreadsheet-based, dynamic mass load model of the Tongue River to use as a tool for evaluating the potential effects of CBNG discharges. The model was calibrated for the period of 2000 through 2003 using historic Tongue River flows and water quality, and measured discharge rates and chemistry of produced water. Additionally, the model was used to estimate the assimilative capacity of the Tongue River to receive CBNG produced water at various in-stream flows. The model employs a Monte Carlo technique to assess potential variability in future stream flows and water quality, and to evaluate downstream compliance with water quality standards.

Approach

The Fidelity NPDES permit authorizing flow-weighted discharge of produced water from CBNG operations differs from conventional NPDES permits in two important ways:

- Effluent limits are developed to control the quantity of discharge water rather than to stipulate the effectiveness of a treatment process.
- Effluent limits (e.g. CBNG discharge rates) vary according to the ambient flow in the river as opposed to using a fixed discharge rate calculated to be protective at extreme low flows.

A spreadsheet-based mass load model was developed to estimate the chemistry that would result downstream of outfalls in the Tongue River for a representative range of flows and associated ambient water quality in the Tongue River. The model uses daily streamflow measured in the Tongue River from 1960 to 2003. Additionally, the model accounts for natural variations in ambient stream chemistry resulting from variations in flow. Finally, the model accounts for random variability in the chemistry of "produced water" (e.g. groundwater pumped by CBNG operations). The following procedure was used to develop flow-based permit limits using the Tongue River dynamic mass load model.

- Develop flow ranges for which allowable produced water discharge rates would be determined.
- Assemble data with a representative range of observed flows and associated Tongue River chemistry, and develop statistical relationship so that ambient chemistry can be predicted from flow.
- Develop statistical distribution of produced water chemistry.
- Create mass load model and calibrate to observed Tongue River flow and chemistry above and below historic Fidelity discharges for 2000 through 2003.
- Use mass load model to assess protectiveness of estimated CBNG discharge rates developed for each flow tier.

Model inputs

The Tongue River dynamic mass load model that predicts water quality downstream of CBNG outfalls is based on the flow and chemistry of two waters that are mixed: the Tongue River and CBNG production water. The model was used to estimate the concentration of EC, SAR (calcium, magnesium, and sodium each modeled individually to estimate downstream SAR), ammonia, fluoride, and key metals downstream of CBNG discharges. Results for EC, SAR, and ammonia are discussed in this paper. The model assumes complete mixing of waters, and also assumes that all modeled constituents are chemically conservative, meaning that no water or chemical mass is gained or lost over the modeled reach. Model calibration indicated that EC, calcium, magnesium, and sodium are chemically conservative, but that ammonia is lost from the Tongue River through volatilization, or biological processes such as nitrification or assimilation.

The model is based on three primary inputs including a daily mean series of ambient streamflow for the Tongue River, estimated ambient Tongue River chemistry that accounts for flow-related variations and for natural statistical variations, and observed statistical variation in CBNG production water chemistry.

Development of flow tiers

Daily average stream discharge has been continuously monitored since September 1960 at the USGS gauging station near the Wyoming-Montana state line (USGS Station 06306300). This gauge is located near the Fidelity outfalls and provides representative streamflow measurements collected over a 41 year period of record that includes several recent drought years. In order to develop flow tiers, a flow duration curve was developed by ordering all available daily flows from lowest to highest. Five flow tiers (**Table 3**) were developed to segment the hydrograph into flow regions, with each tier having unique effluent limits and allowable CBNG discharge rates.

Table 3. Flow tiers proposed for the Fidelity NPDES permit.

Flow Tier	Flow Range (cfs)		Design Limit [1]	Percentage of time that flow is less than upper range of flow tier	
	Low	High		Incremental	Cumulative
1	0	50	35	1.1%	1.1%
2	50	120	50	9.7%	10.8%
3	120	200	120	25.2%	36.0%
4	200	350	200	33.7%	69.6%
5	350	∞	350	30.4%	100.0%

[1] – Tongue River flow rate used for calculating effluent limits in each flow tier.

Dynamic model of ambient Tongue River streamflow and chemistry

Water quality samples were collected periodically by the USGS at station 06306300, providing a sample database that can be used to simulate ambient water quality. The concentration of the most common ions changes with streamflow. Lower concentrations are associated with peak runoff, and higher concentrations occur during low flow periods. Streamflow typically varies seasonally by a factor of 10 or more, while common ion concentrations may vary seasonally by a factor of 3 to 5.

An empirical equation was developed to relate Tongue River streamflow to water quality [1]. The equation assumes that below a threshold flow (Q_t), water is contributed by groundwater, which has a constant chemistry (C_{bf}). Above the threshold flow, the concentration is determined by assuming that chemical load provided by base flow remains constant, and is mixed with runoff and interflow that has a lower concentration (C_{ro}). The terms Q_t; C_{bf}, and C_{ro} were determined from USGS water quality data using a least-squares regression technique (Pezzullo, 2002).

$$C_q = C_{bf} \text{ for } Q<Q_t;\ C_q = [(C_{bf} * Q_t)+(C_{ro} * (Q-Q_t)] / Q$$ [1]

Where C_q is the concentration in receiving water upstream of discharges at a specific flow,

C_{bf} is the concentration of upstream receiving water during low flows,

C_{ro} is the concentration of upstream receiving water during high flows,

Q_t is the flow threshold separating low flow and high flow regimes.

Only pre-1999 USGS data was used in creating the empirical flow-chemistry relationships (**Figure 1**). A non-linear least-squares curve fitting routine (Pezzullo, 2002) was used to calculate the variables in equation 2 based on observed water quality and flow at the USGS station. Separate equations were also developed that corresponded to the median, 10th, and 90th percentile of the distribution. The correlation coefficient (r) for these curves varied from 0.87 to 0.97 meaning that the equations are able to describe most of the statistical variation in the concentrations of EC, calcium, magnesium, and sodium on the basis of measured flow (**Table 4**). The flow-based SAR was determined using the estimated calcium, magnesium, and sodium concentrations.

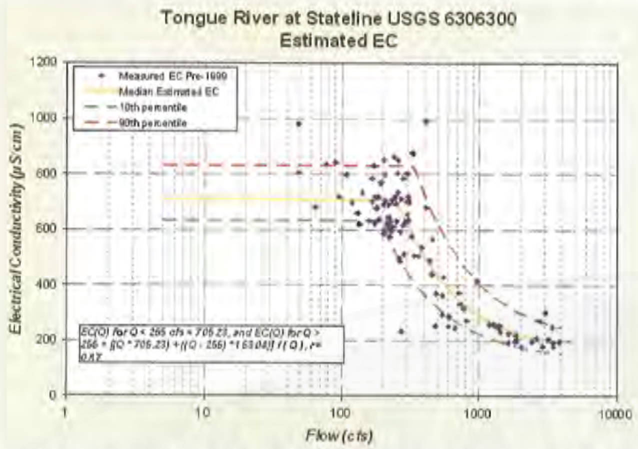

Figure 1. Curve fit for flow-based equation for electrical conductivity.

Table 4. Empirical coefficients for flow-based estimates of ambient stream chemistry.

Empirical model coefficient for determining ambient water quality from flow	Water quality parameter			
	Electrical conductivity	Calcium	Magnesium	Sodium
Threshold flow – Qt (cfs)	254.9	187.1	182.1	172.7
Concentration of baseflow – Cbf (mg/L)	705.2	69.3	43.75	32.0
Concentration of runoff – Cro (mg/L)	153.0	18.35	4.91	3.12
Correlation coefficient	0.87	0.97	0.96	0.91
Number of observations	108	25	25	25

Produced water chemistry

The water quality of Fidelity CBNG production water has been extensively sampled and characterized. Discharge Monthly Reports have been submitted to the State for more than 3 years, and contain 400 water quality measurements (**Tables 1** and **5**). The population distribution for selected constituents was fit to numerous standardized distributions using Palisade BestFit©, a macro that works within Microsoft Excel©. The statistical distributions that provided the best fit were generally normal or log-normal. The resulting expression for each population distribution in the format of the stochastic modeling package (Palisade @Risk©) is also shown in **Table 5**.

Tongue River dynamic mass load model

Model structure

To determine the potential effects of the historic discharge of produced water on EC and SAR values in the Tongue River, a mass load model was developed to account for the variations in Tongue River stream flow and chemistry. The model is based on a mass balance principal [2] where the downstream concentration can be estimated from the flow and concentration in the upstream receiving water, and the flow and concentrations in the discharge water.

$$C_{down} = [(C_{rw} * Q_{rw}) + (C_{pw} * Q_{pw})] / (Q_{rw} + Q_{pw}) \quad [2]$$

Where C_{down} is the estimated concentration in receiving water downstream of the mixing zone where complete mixing occurs,

C_{rw} is the concentration in receiving water upstream of discharges,

Table 5. Measured water quality in CBNG production water from the Fidelity CX Field including calculated mean, standard deviation, best fit statistical distribution, and @Risk representation of the population distribution.

Constituent	Mean	Standard Deviation	Best Fit	Equation
Lab EC (µS/cm)	1970	193	normal	normal RiskNormal(1970.02, 193.27)
pH (SU)	7.85	0.28	normal	RiskNormal(7.85036, 0.27574)
Ammonia (mg/L)	1.78	0.35	lognormal	RiskLognorm(6.3759, 0.34455, RiskShift(-4.6009))
Calcium (mg/L)	4.94	4.59	lognormal	RiskLognorm(4.1021, 1.5831, RiskShift(0.71129))
Magnesium (mg/L)	1.93	7.06	lognormal	RiskLognorm(1.1914, 0.69455, RiskShift(0.45062))
Sodium (mg/L)	501	56	normal	RiskNormal(500.711, 55.785)

Q_{rw} is the flow of upstream receiving water,

C_{pw} is the concentration of produced water,

Q_{pw} is the flow or discharge rate of produced water.

The computation sequence used in the spreadsheet model follows.

1. The basic model input consists of daily flow measured at the USGS gauging station, Tongue River near state line (06306300), for the period of record from September 1960 to the end of 2003.
2. The estimated ambient chemical concentration in the Tongue River (up-gradient of CBNG discharges) is estimated from equation [1] using coefficients described in **Table** 4.
3. The available data pairs for Tongue River flow and concentration exhibit some variability around the line described in step 2 (equation [1]). This random variation was simulated by multiplying the value derived in step 2 by a factor that is selected from a log-normal population with a mean of 1.0, a standard deviation of 0.15, and minimum and maximum values of 0.5 and 2.0 respectively. A degree of temporal autocorrelation was incorporated in the model by forcing consecutive daily concentrations to have a correlation of 0.9. Simulation of this temporal autocorrelation is particularly important in the Monte Carlo model to better simulate 4-day average and 30-day average receiving water concentrations.
4. Next, the quantity of CBNG production water is input from a table of values containing permissible discharge quantities for each flow tier. The permissible discharge quantity for a flow tier is determined using a mass load mixing calculation using 75th percentile ambient water quality, the design flow for each flow tier (see **Table 3**), and median CBNG production water chemistry.
5. Next, the concentration in produced water is selected stochastically from a population distribution developed from historic monitoring data. A macro language distributed by Palisade, called @Risk© was used for the stochastic elements of the model.
6. The estimated concentration downstream of the zone where complete mixing occurs (called the receiving water concentration or RWC) is calculated from Tongue River and CBNG flow and chemistry according to the mass balance equation: $C_{RWC} = [(C_{TongueRiver} * Q_{TongueRiver}) + (C_{CBNG} * Q_{CBNG})] / (Q_{TongueRiver} + Q_{CBNG})$.
7. For purposes of estimating compliance with water quality standards, the daily values for concentration below the zone of mixing can be summarized for various averaging periods. The model reports daily, 4-day average values, and 30-day average values that correspond to averaging periods specified in Montana water quality rules for compliance purposes (MDEQ, 2003).

Calibration using 2000 through 2003 monitoring data

The dynamic Tongue River mass load model was calibrated using flow data from 2000 through 2003. During this time period, Fidelity was discharging 500 to 1500 gpm (1.1 to 3.3 cfs) of production water. Water quality down-gradient of the discharged water was measured monthly by Fidelity and periodically by USGS. A comparison of the modeled and measured electrical conductivity values is shown in **Figure 2**. During the calibration period, flows ranged from 10 cfs (below the 7Q10 of 35 cfs) to 3000 cfs. The model provided close agreement to measured EC values downstream of discharges, with lower values occurring during periods of high flow, and higher values during low flows. Comparison of measured and estimated values (**Figure 3**) shows estimated EC values were generally within 100 μS/cm

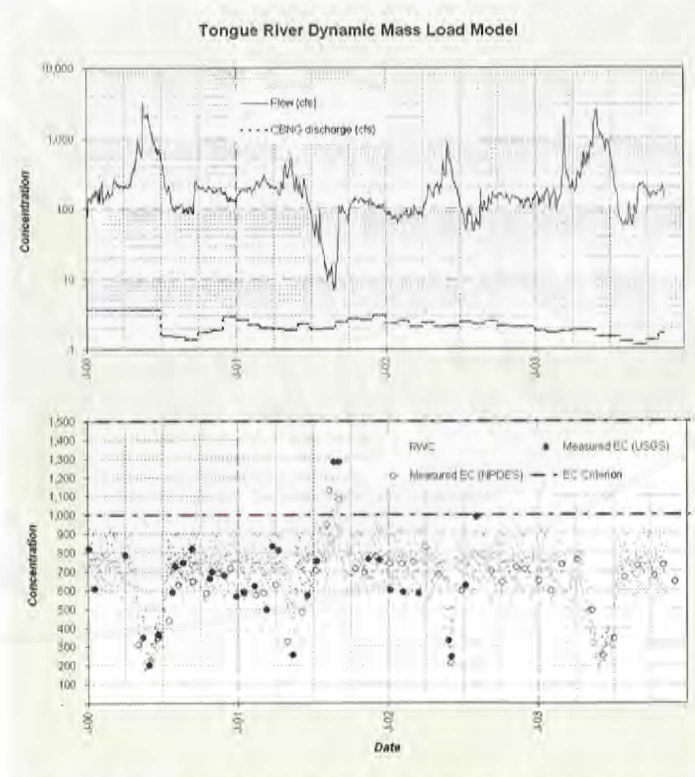

Figure 2. Tongue River flow and CBNG discharge rate (above); and comparison of measured and estimated EC values.

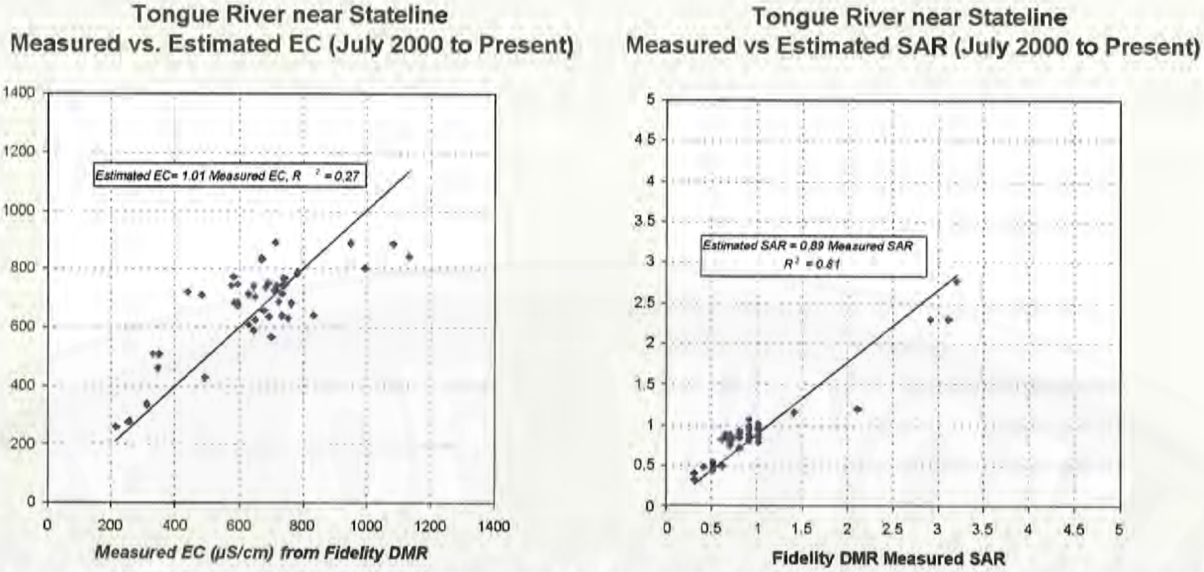

Figure 3. Comparison of measured and estimated SAR values downstream of the Fidelity discharges.

of measured values and estimated SAR was within 0.5 units of measured. The small difference between individual estimated and measured values was due to the random variability in water quality. The overall correlation of estimated and measured values is good, and has a slope very close to 1.0.

Montana's numeric water quality standards were not adopted until 2003. For the previous 3 years, the Fidelity permit was fully protective of the numeric standards, even though the permit limits were based on narrative standards. This finding demonstrates that the Tongue River has continued to support all beneficial uses while CBNG waters have been directly discharged to the river. Further use of the dynamic mass load model, described below, shows that the Tongue River has ample assimilative capacity for additional CBNG water without impairing ambient water quality.

Estimating assimilative capacity of the Tongue River

For each flow tier described in **Table 3**, the maximum potential CBNG discharge rate was calculated. A simple mass load calculation was used to calculate maximum discharge rate for the lowest applicable flow within each flow tier. As allowed by State law, the 7Q10 was used as the design flow in Tier 1. For all other flow tiers, the design flow was the lowest applicable flow in the range. The maximum discharge rate provides an indication of the assimilative capacity of the Tongue River for CBNG water.

The maximum CBNG discharge rate was calculated for each constituent. The ambient concentration in the Tongue River was assumed to be the upper 75th percentile for a given flow. The median chemistry was used for the CBNG water. The maximum discharge rate is calculated by solving for the CBNG rate that brings the mixture of waters up to the applicable water quality standard. Since the Tongue River is currently well below standards for these constituents, the river has the ability to assimilate the load associated with additional CBNG production water without exceeding water quality standards.

The allowable levels of ammonia, fluoride, EC, and SAR were based on Montana's water quality standards including their non-degradation provisions. The allowable concentrations of ammonia and fluoride are 15 % of the water quality standard. For ammonia, the non-degradation limit was 0.14 mg/L and 0.22 mg/L for summer and winter months respectively. The EC and SAR limits are 1000 µS/cm and 3.0 respectively, as described in **Table 2**. Ammonia was the most limiting constituent contained in CBNG water, and therefore determines the permissible CBNG discharge rate.

The Tongue River dynamic mass load model was run using the maximum permissible discharge rate from **Table 6** to determine the downstream effect of discharging this maximum potential quantity of production water over a long period of record and wide range of flows. The model was run using a Monte Carlo stochastic routine in which 500 model iterations were performed. For each iteration, water quality data for the Tongue River and produced water were independently determined from their respective statistical distributions. The Monte

Table 6. Calculated maximum allowable CBNG discharge rate for each flow tie based on each potentially limiting constituent in CBNG water.

Tier	Tongue River			Maximum Potential Produced Water Discharge (gpm) based on individual parameters				Lowest produced water discharge rate based on most limiting constituent (Annual average)
	Lower Flow (cfs)	Upper Flow (cfs)	Percentage of Time in Flow Range	Ammonia Winter (Sep-May)	Ammonia Summer (Jun - Aug)	Electrical Conductivity	SAR	
				Applicable water quality limit				
				0.22 mg/L	0.14 mg/L	1,000 µS/cm	3.0	
1	0	50	1.09%	1623	794	3404	3208	1415
2	50	120	9.66%	2318	1134	4863	4584	2022
3	120	200	25.0%	5564	2722	11,670	11,001	4853
4	200	350	36.7%	9273	4536	31,310	18,867	8088
5	350	∞	27.6%	16,227	7938	101,070	28,929	14,155
Annual Average (gpm)								
			100%	9508	4651	42,775	18,126	8294

Carlo analysis provides a range of probable receiving water concentrations. **Figure 4** presents the 10th, 50th, and 90th percentile EC values in the Tongue River estimated by the model for instantaneous measurements (upper **Figure 4**) and 30-day average values (lower **Figure 4**). These values are compared to ambient Tongue River EC values and applicable EC criteria. Because of the discharge of CBNG water, very little net change in EC is projected by the model since ammonia is the most limiting constituent.

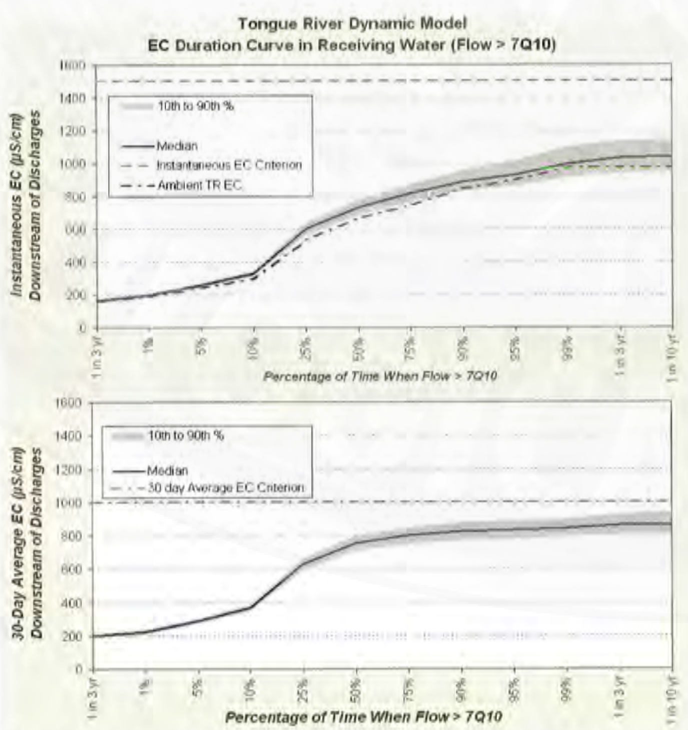

Figure 4. Model estimated 10th, 50th and 90th percentile downstream EC values when CBNG production water is discharged at the maximum potential rate. Water quality criteria are met for all conditions.

The resulting downstream water quality was compared to applicable Montana water quality standards to determine whether discharge of the maximum quantity of CBNG water would cause the Tongue River to exceed standards (**Table 7**). The model-estimated Tongue River water quality results showed that discharge of an average of 8294 gpm of production water would not impair Tongue River water quality.

Discussion

The assimilative capacity of the Tongue River for CBNG production water is even greater than the value determined by the mass load model, because the limiting constituent, ammonia, is not chemically conservative in the Tongue River. Monitoring data below the Fidelity discharges indicates that the relatively low concentrations of ammonia (approximately 2 mg/L) in produced water are lost from solution within a short distance of the outfalls. Removal may occur by any of a number of mechanisms including volatilization, sorption/ion exchange on bed sediments, nitrification, or assimilation. For the next most limiting constituents, fluoride and SAR, an average of 14,000 to 18,000 gpm of CBNG water could be safely discharged without impairing beneficial uses or exceeding water quality standards. The additional water would increase the flow in the Tongue River by about 8% from average annual conditions.

The Tongue River mass load model is a useful decision support tool for industry, permit writers, and other regulatory purposes. For example, a total maximum daily load (TMDL) is being considered for key constitu-

Table 7. Estimated water quality compliance in the Tongue River assuming that produced water is discharged at the maximum potential rates listed in Table 12.

Constituent	Averaging Period		
	Instantaneous	4-Day Average	30-Day Average
Electrical Conductivity (µS/cm)	Always < 1,500 µS/cm	NA	Always < 1,000 µS/cm
SAR	Always < 4.5	NA	Always < 3.0
Winter Ammonia as N (mg/L)	NA	Less than 2.5 times the acute level (Criterion Maximum Concentration or CMC)	Always < 0.22
Summer Ammonia as N (mg/L)	NA	Less than 2.5 times the CMC	< 0.14 for more than 99% of time

ents in the Tongue River including EC and SAR. While a watershed model has been developed for simulating surface water hydrology and chemical loads, a simple spreadsheet model may provide useful validation of the water quality targets and load allocations developed in the TMDL process.

Conclusions

- A dynamic model was developed to estimate daily and 30-day average values for ammonia, EC, and SAR downstream of Fidelity discharges. The model was calibrated to measured flows and chemistry for the period from 2000 through 2003. There was good agreement between estimated and measured values.
- The model agrees with historic water quality monitoring data and shows that the current Fidelity NPDES discharge permit (MT-0030457), approved in 2000, has maintained downstream EC and SAR levels below criteria specified in the recently promulgated numeric standards for EC and SAR during the entire span of the permit.
- The Tongue River dynamic mass load model uses Monte Carlo simulation techniques to evaluate mixing of Tongue River water and produced water. The model considers the flow-dependent chemical distribution of ion concentrations in upstream (ambient) Tongue River water and accounts for the random variation in the chemistry of produced water.
- Five hundred dynamic model iterations were run for each constituent. Each iteration consisted of 15,779 daily estimates of receiving water and produced water flow and chemistry, computed at the maximum potential produced water discharge rates. Constituents in produced water that have the potential to affect receiving water quality included EC, SAR, fluoride, and ammonia. Ammonia was found to be the most limiting constituent.
- Model results showed that the Tongue River can assimilate from 8000 to 18,000 gpm of produced water while preserving downstream water quality and meeting all relevant water quality standards.

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Modeling the assimilative capacity of the Powder River Basin, Wyoming

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Joe Olson–Williams Production Company, Gillette, Wyoming

Under the Clean Water Act and Wyoming water quality regulations, additional loading to the Powder River due to discharge of water produced by coalbed natural gas wells may be allowable. To assess the incremental allowable volumes, the Petroleum Association of Wyoming (PAW) tasked CBMA to model the assimilative capacity of the Powder River in Wyoming.

The regulatory drivers to this assessment include Section 20 of the Wyoming regulations, the new Montana standards, and ambient water chemistry. As there is no irrigation use in Wyoming to consider, a Section 20 evaluation is not needed. Ambient water quality during drought conditions is a likely limiting factor. The Montana standards for electrical conductivity (EC) and sodium adsorption ratio (SAR) are limiting factors when ambient conditions exceed these standards.

The model that CBMA developed is an extension of work previously done by Art O'Hayre of Applied Hydrology in 2002 and 2003 for PAW. Dr. O'Hayre's model was based on USGS methodology for estimating total dissolved solids (TDS) or EC at Powder River stations located at Sussex and Arvada, Wyoming and Moorhead, Montana, using a spreadsheet base. The extension uses linear regression to estimate calcium, magnesium, and sodium concentrations from TDS at Moorhead, and then calculates a SAR value.

Given the Montana EC and SAR standards under average monthly conditions, this model was used to compute allowable average monthly Big George CBNG well discharge rates that range from 13 to 178 cubic feet per second. With these flows, the Hansen no-risk SAR values ranged from a low of 5 in June to 12.6 in December.

For a risk-based approach, the model was used to estimate the allowable average monthly Big George discharge rates given the Montana EC limits. Under this condition, the allowable rates varied from 32 cfs in August to 1049 cfs in June. Hansen no-risk SAR values were 10.1 in the irrigation season, and 13.4 in the winter season; simulated SAR values ranged from 6.1 to 9.9 in the irrigation season, and from 7.8 to 10.1 in the winter season.

Preliminary results of a study of infiltration from an impoundment for coalbed methane water, Powder River Basin, Wyoming

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Timothy T. Bartos–U.S. Geological Survey, Cheyenne, Wyoming
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The U.S. Bureau of Land Management estimates that by the year 2010 there may be as many as 50,000 coalbed methane producing wells in the Wyoming part of the Powder River Basin (PRB). The fate of water developed with the natural gas and its impact on the environment are topics of some concern. The federal Environmental Impact Statement cites use of surface impoundments as a preferred alternative for containment of the water. As of April 2004, the Wyoming Department of Environmental Quality had permitted approximately 2900 impoundments in the PRB. The U.S. Geological Survey initiated a study of infiltration from one of these impoundments in 2003. Sediment core samples (for physical and chemical analyses) from beneath Skewed Reservoir were obtained prior to filling. Water extracts of these sediment samples were analyzed for leachable concentrations of chloride, nitrate, and sulfate. Suction lysimeters were installed at depths of 10, 16, and 22 ft beneath the base of the impoundment and were used to obtain monthly pore water samples after the reservoir began accepting water. Preliminary results indicate that as CBM discharge water moves through the subsurface it is dissolving naturally occurring soluble sodium-magnesium-sulfate salts in the sediments. The infiltrating water acquires chemical characteristics unlike the impounded CBM water or the native shallow ground water. A solute plume with total dissolved solids in excess 70,000 mg/L has been created in the shallow subsurface.

Preliminary observations on the geochemistry of the shallow alluvial aquifer in a drainage with CBM development

Karl Taboga, Rachel Toner, Frank Sanders, Buster Ivory, and Gretchen Kohler–CBM Associates, Inc., Laramie, Wyoming

Hydrologic and geochemical studies in coalbed methane (CBM) developed and non-developed watersheds are ongoing in NE Wyoming (see Sanders and others, this volume, pages 6-12). Included in the study of developed watersheds is LX Bar Creek, an ephemeral tributary of the Powder River located in northeastern Campbell County. Available data on ephemeral watershed hydrology in NE Wyoming suggest that surface discharge from infrequent summer thunderstorms and spring snowmelt runoff should flush residual water stored in intermittent surface potholes in LX Bar Creek and result in relatively low salinity water stored in such potholes following flushing events. Recent observations on the chemistry of pothole water in LX Bar Creek indicate that, in general, sampled potholes have relatively high salt concentrations. Although pothole flushing has been reduced during the current drought cycle, these observations suggest that pothole water is originating either from higher salinity alluvial groundwater which may or may not include CBM-related salts from upgradient discharges, or from short-runout storm flow (e.g., short distance surface flow in the ephemeral channel and from near-field hillsides) that transports soluble constituents from surface materials.

Subsequently, a study of shallow alluvial aquifer geochemistry was initiated to explore the possible mechanisms controlling the geochemistry of water found in surface potholes. The goal is to distinguish between naturally occurring weathering and transport processes versus CBM-derived salts on downstream water quality. This project seeks to answer two questions: 1) Is the alluvial aquifer the primary source water for surface potholes; and 2) does CBM discharge water affect the geochemistry of the alluvial aquifer or surface potholes?

Eighteen shallow monitoring wells were installed along LX Bar Creek during summer 2003 to allow spatial monitoring relative to subsurface geology (especially confining lens) underlying the alluvium/colluvium deposits of the stream channel and to possible CBM-derived loadings of salts to alluvial groundwater. The wells were located along the drainage in areas immediately adjacent to monitored pothole locations and in locations where no potholes have previously been observed. Several wells were paired to assess the lateral extent of shallow groundwater from the stream channel outward to the first large depositional terrace.

The monitoring wells, influent CBM outfalls, and surface pothole water have been sampled regularly for major ion chemistry during a period of two years. Samples from these sources also were analyzed for radiogenic strontium ratios to define the origins of water to the shallow aquifer and surface potholes.

Preliminary data from the major ion analyses show close correlation between groundwater samples and streambed potholes. The geochemistry of CBM discharges varied markedly from streambed/monitoring well samples. Data from the strontium study were widely scattered and did not fall along a mixing line. Strontium ratios showed wide variations within wells in close proximity to one another. In summary, results of this preliminary study suggest that the shallow alluvial aquifer is a complex anisotropic system typified by localized geochemical cells. The water of origin for each monitoring well and near-by monitored potholes is difficult to evaluate based on local heterogeneity but there is no strong indication of CBM-related influences. Further study is required to evaluate the influence of CBM discharges, if any, on the chemistry of surface potholes and therefore potentially on downstream water quality during flushing events.

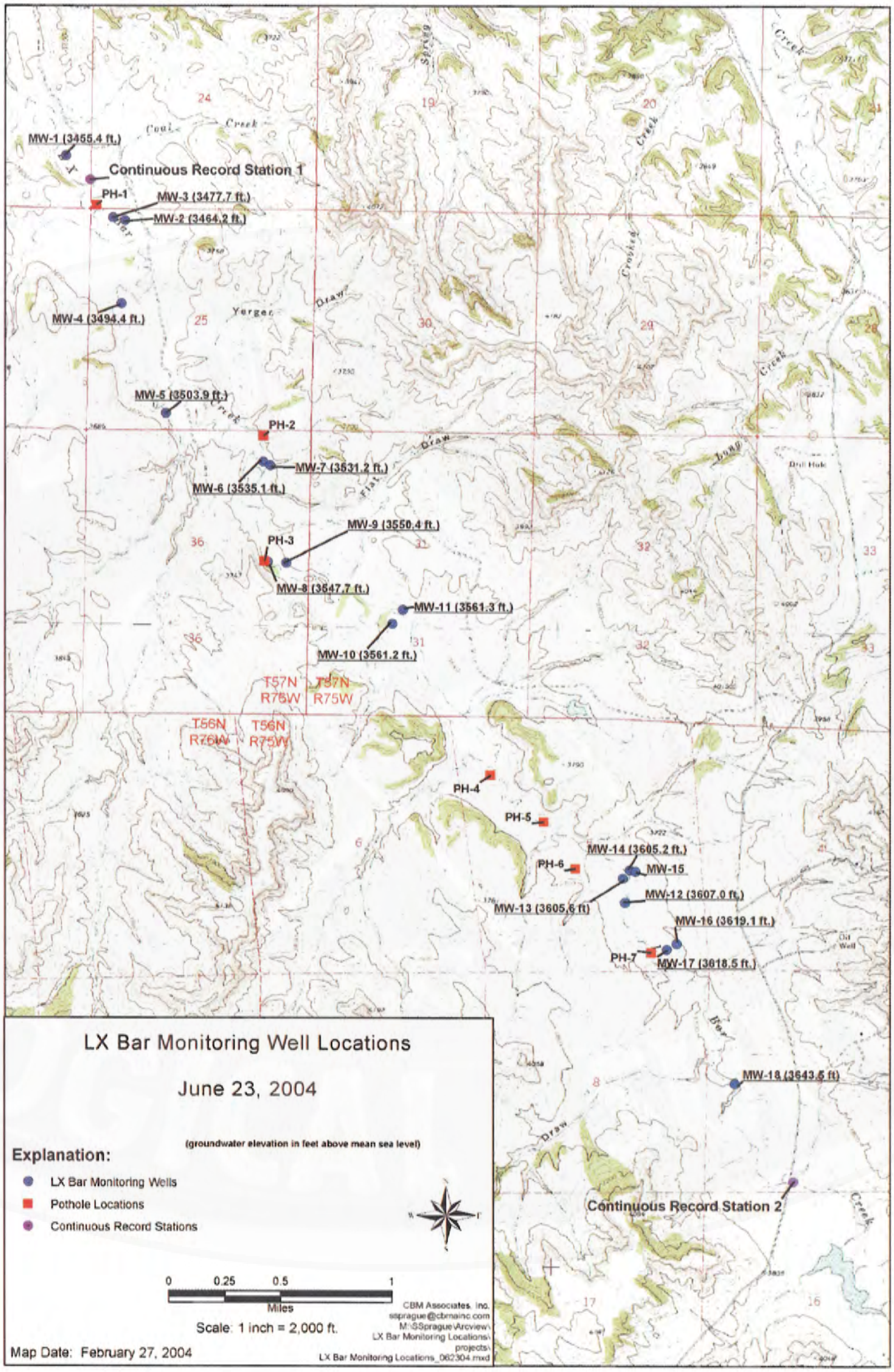

Figure 1. Map of LX Bar Creek Study Site with sampling locations shown.

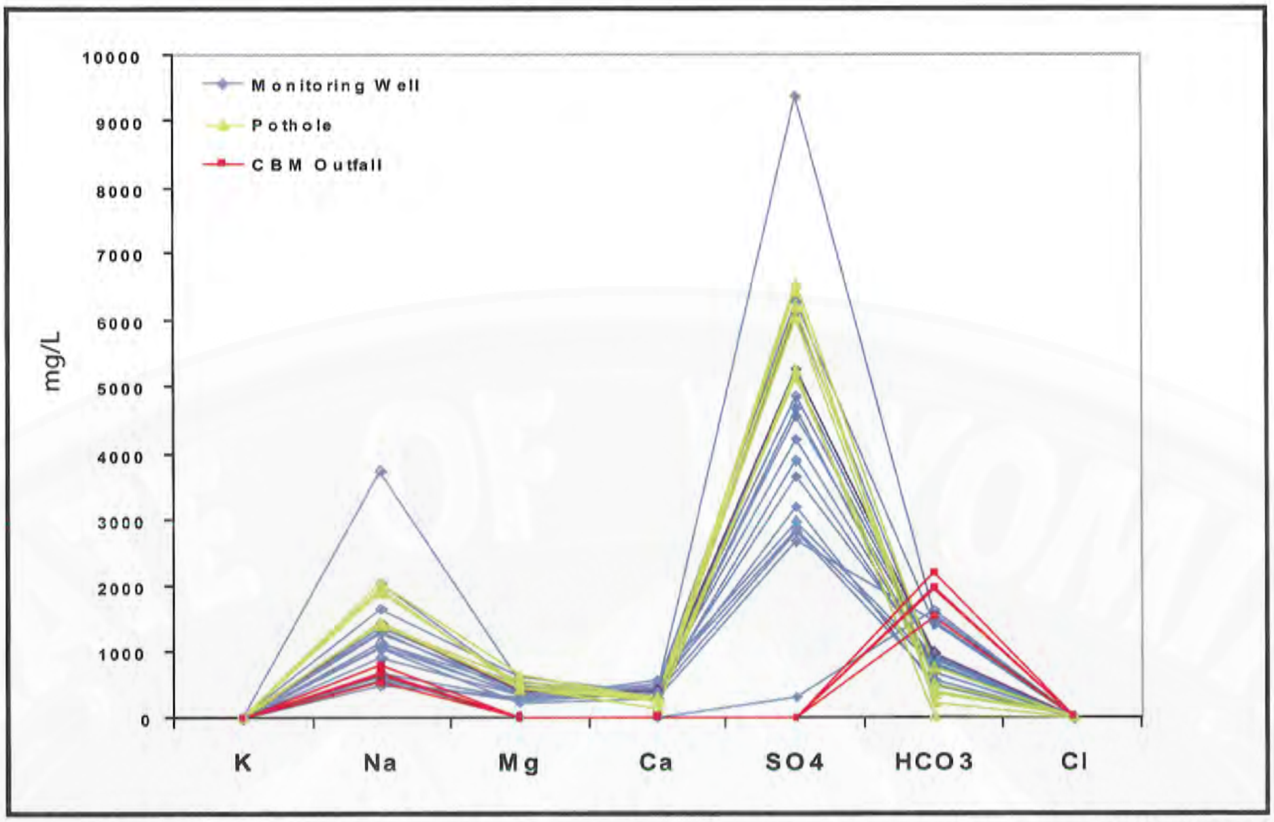

Figure 2. Geochemical fingerprint of waters from shallow alluvium, surface potholes and CBNG discharge.

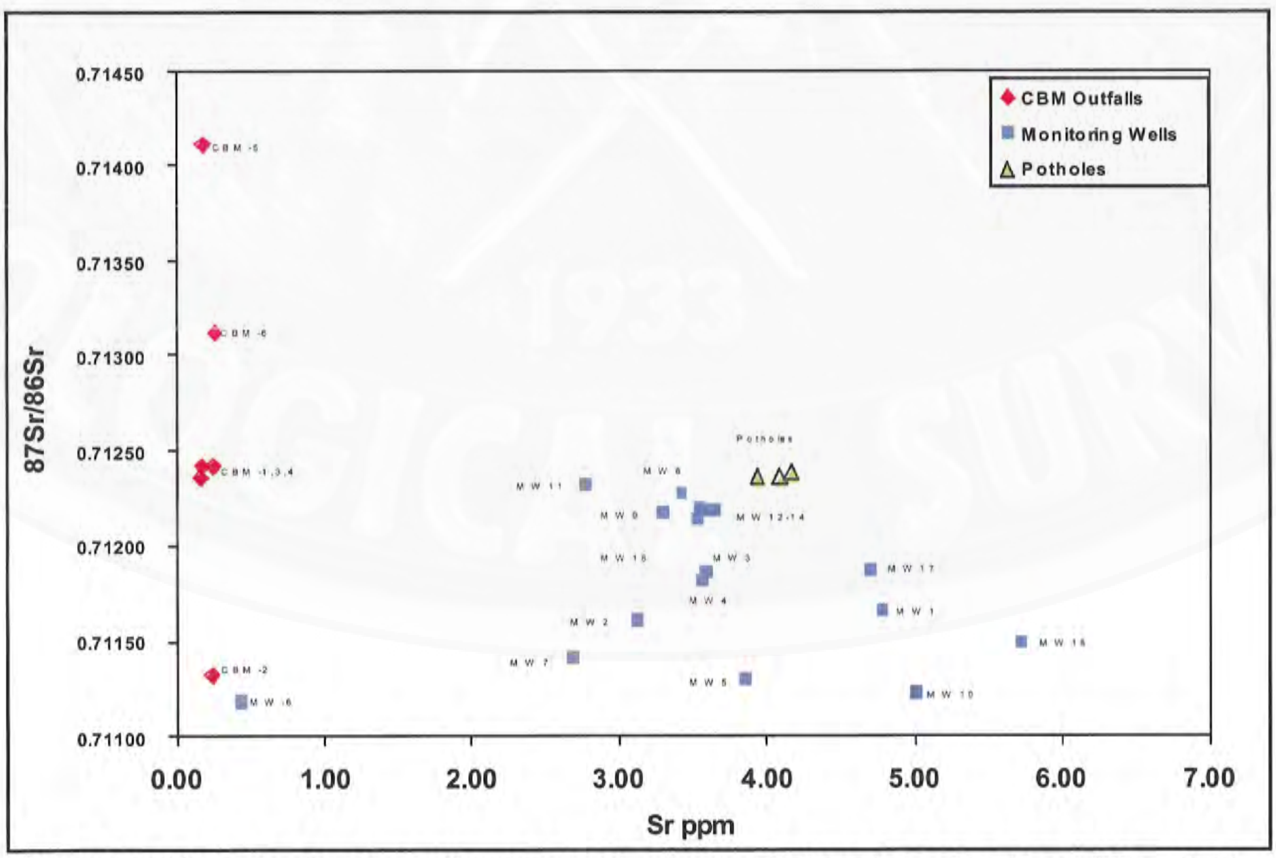

Figure 3. Radiogenic strontium ratios vs. strontium concentrations for waters from LX Bar Creek.

Preliminary changes in groundwater quality related to coalbed methane infiltration ponds

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Andy Bobst–U.S. Bureau of Land Management
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Coalbed methane is being produced from Tertiary coal beds in the Powder River Basin in southeastern Montana and northeastern Wyoming. Methane production requires pumping water from the coal beds to reduce hydrostatic pressure, thus allowing the gas to desorb and be collected at wells. The produced water must be managed in a manor that is both environmentally responsible and economical. One water-management method is to discharge the water to infiltration ponds where the water is lost to evaporation (3 to 4 feet per year), infiltration, and in some cases release to surface water.

Water that infiltrates from coalbed methane ponds will eventually migrate to and recharge underlying aquifers, or if controlled by aquitards it will flow horizontally and discharge at land surface. Coalbed methane production water is rich in sodium and can contain high concentrations of dissolved salts due to chemical reactions along flow paths after leaving the ponds. Concerns about impacts to ground-water resources has lead to research intended to develop and confirm models for predicting changes in water quality. The conceptual models that are being tested are based on research of coal mine hydrogeology conducted since about 1970. The results of research on infiltration ponds can be used to help avoid unsuitable locations.

Data from four ponds (one in Montana, three in Wyoming) indicate that concentrations of calcium, magnesium, and sulfate will increase along ground-water-flow paths. The result is water with a lower sodium adsorption ratio and higher concentration of total dissolved solids than the original coalbed methane water. The duration and magnitude of the increases are functions of the geology at the site. Decreases in these changes, due to flushing of salts, has not yet been documented at infiltration ponds.

The data collected as part of this program are available to the public on the Internet through the Montana Ground-Water Information Center <http://mbmggwic.mtech.edu>.

Tracking CBM infiltration pond impacts upon groundwater using strontium isotopes

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Disposal of water from coalbed methane (CBM) production is an important environmental, agricultural, and legislative issue. Current practice in the Powder River Basin of Wyoming and Montana includes collecting the water in infiltration ponds both in and off existing drainages. Discharge from these ponds is by means of infiltration and evaporation. Recent data indicate that these ponds have the potential to negatively impact underlying groundwater. This observation is important because Wyoming regulations require that the class of use of groundwater be protected in all situations. Our study looks at an off-channel infiltration pond in the Coal Creek area near Ucross, Wyoming and two in-channel ponds in the Beaver Creek area near Gillette, Wyoming. We have used hydraulic measurements, major ion chemistry, and strontium (Sr) isotope data to:

1. Distinguish CBM water from surface and shallow groundwater
2. Trace the infiltration of CBM water
3. Identify the effect of CBM water upon water quality in surface and shallow groundwater
4. Determine if the effect on water quality is dependant upon local, pre-existing conditions by comparing:
    a. Arid, off-channel, infiltration ponds
    b. In-channel discharge into existing water drainages

CBM production and subsequent water discharge into the Coal Creek pond began in December 2003. As of June 2004 over 10 million gallons of water have been added to the pond. Before filling began, monitoring wells at varying depths were installed within and surrounding the pond, and along nearby Coal Creek. Prior to the release of CBM production water, the groundwater table was 17 feet below the floor of the pond. After 6 months of discharge into the pond, the groundwater level has risen 13 to 23 feet. The infiltrating CBM water at the Coal Creek site has caused an eight-fold increase in total dissolved solids (TDS) in groundwater at a depth of 23 feet below the floor of the pond.

The strontium concentration in conjunction with the ratio of radiogenic 87-Sr to 86-Sr has been shown to be an effective fingerprint that distinguishes CBM water from other ground and surface water. This is true in both the Coal Creek and Beaver Creek areas. In Coal Creek the CBM wells produce water with a ratio of 0.711 while the local ground and surface waters of the perennial Coal Creek have a more radiogenic signature of 0.714. This difference is shown in **Figure 1**, where the CBM sample is represented by the diamond, the stream samples by squares, and the pond wells by triangles. Within the off-channel pond, the strontium isotope ratio varies from the 0.711 CBM input water at the surface to 0.712 within 0.25 feet of the pond floor, to 0.713 in a shallow well within the pond. Wells within the pond at 23 and 36 feet below the floor show little shift in ratio as of six months after filling began (**Figure 2**). Near the bottom of the pond the CBM strontium is already being diluted by the strontium in the soil by one-third, while in the shallow well the dilution is by two-thirds. The strontium concentration has increased in the middle well (23 feet) but not in the deepest well (36 feet). The stratigraphy shows an aquitard between these two wells, which would account for the delay. We would expect to eventually see similar shifts in concentration in the deepest well.

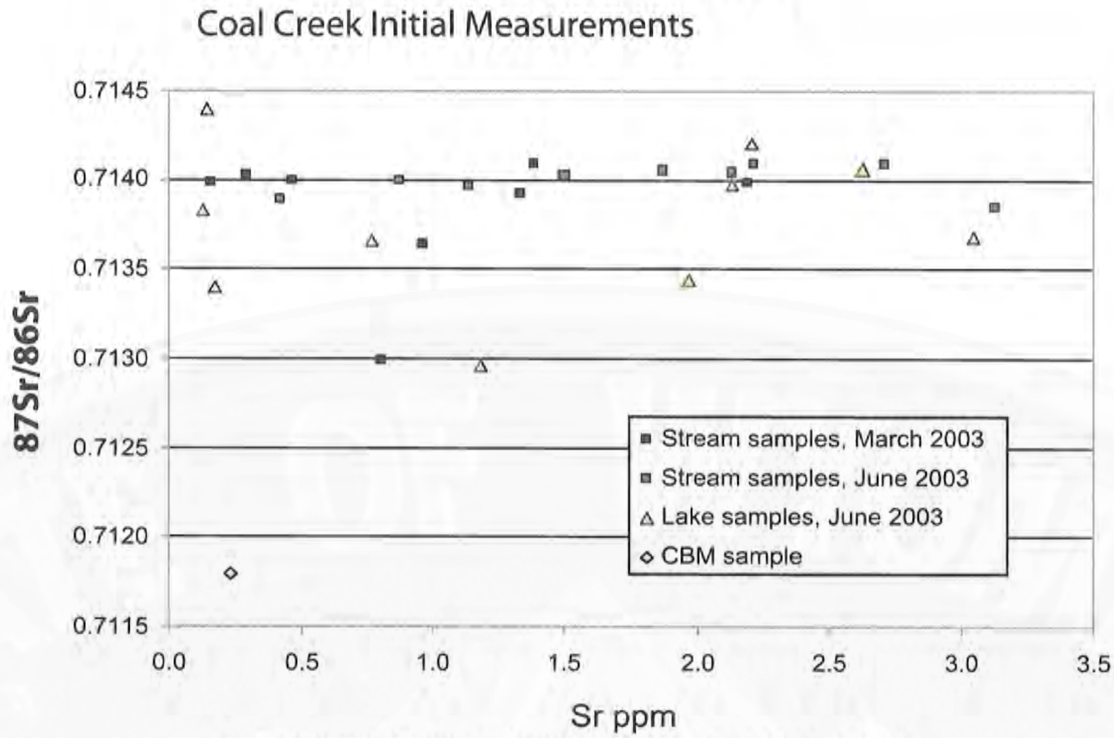


Figure 1. Coal Creek, strontium ratio vs. concentration.

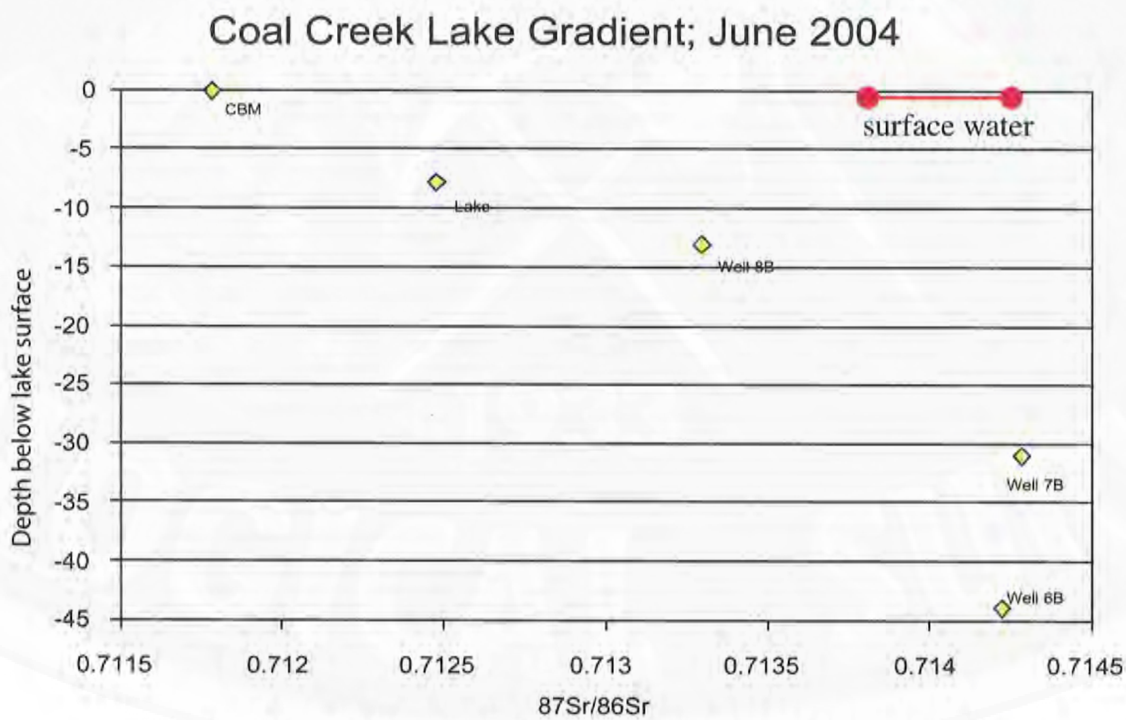


Figure 2. Coal Creek, depth from pond surface vs. strontium ratio.

In the ephemeral tributary of Beaver Creek, the opposite trend is found. Here the CBM water is more radiogenic (a higher 87-Sr to 86-Sr ratio) than the local groundwater. In **Figure 3** the CBM water is represented by the turquoise/open squares, and the base line shallow groundwater (water unaffected by CBM input) by dark blue diamonds. The difference between the two of 0.002 is easily distinguished (analytical error on 87-Sr/86-Sr are ±0.00001). The pink squares in **Figure 3** represent wells that are between the two in-channel ponds. They represent mixing of strontium from CBM input with strontium from the shallow aquifer. The yellow triangles represent the wells that are below both ponds and are slightly off-channel. Over time, these samples have

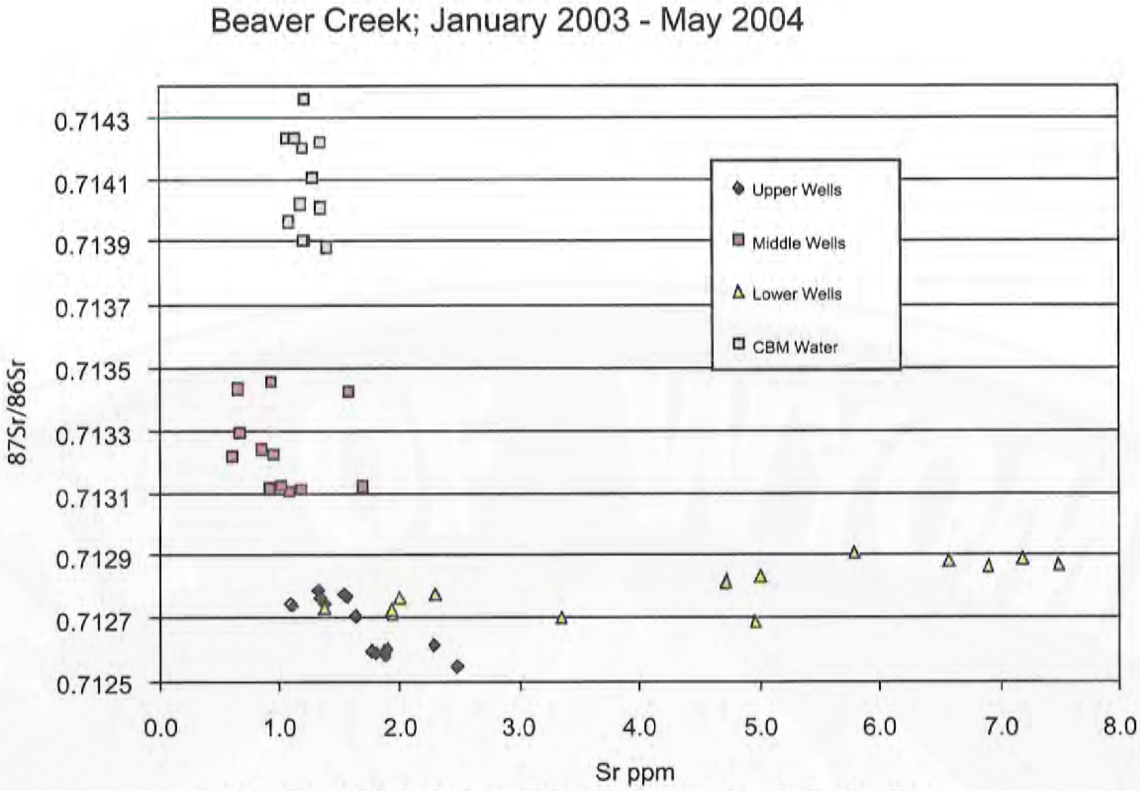


Figure 3. Beaver Creek, strontium ratio vs. concentration.

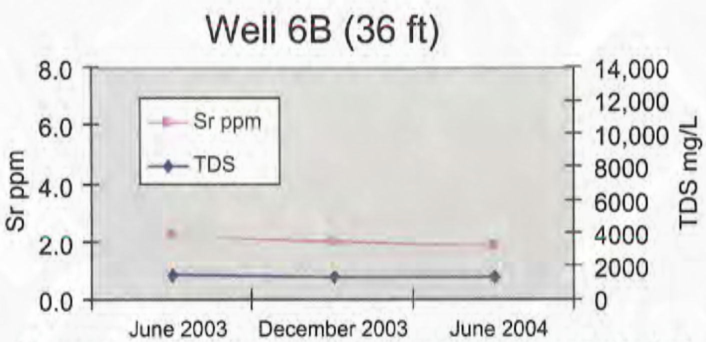


Figure 4. Coal Creek, well 6B strontium concentration and TDS changes with time.

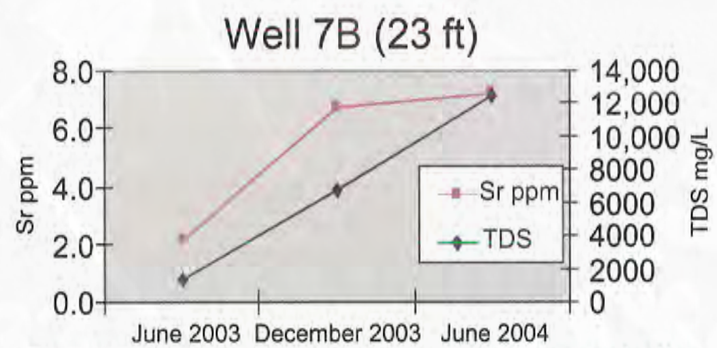


Figure 5. Coal Creek, well 7B strontium concentration and TDS changes with time.

shown a slight increase in ratio towards that of the CBM water in addition to the significant increase in concentration. We interpret the increase in strontium concentration to solution of salts in the alluvium as CBM water infiltrates.

In order to look at how strontium can be used to indicate changes in water quality we look at how the strontium has changed in relation to the corresponding changes in TDS. For the two deepest wells within the Coal Creek pond, the changes in strontium concentration mirror the changes in TDS, including the rapid increase in TDS in the well 23 feet below the pond floor (**Figures** 4 and 5). This is also true for the alluvial wells at the Beaver Creek site. The concentration in the middle well site is decreasing perhaps due to soluble salts being flushed out of the local system. In contrast, the concentration at the lower site is increasing perhaps because less flushing has occurred at these off-channel well sites (**Figure** 6).

In order to compare the effect of CBM discharge upon groundwater at off-channel and in-channel sites, we look at the most dramatic increases at Coal Creek and Beaver Creek (compare **Figure** 5 and **Figure** 6, well 14). It is clear that the eight-fold increase at Coal Creek is significantly more than the two-fold increase at Beaver Creek. This preliminary observation suggests that groundwater quality degradation may be more pronounced at off-channel sites where little natural flushing has occurred prior to CBM development.

Strontium has been shown to be a promising tracer for following the infiltration of CBM produced water. The differences found between Beaver Creek and Coal Creek warrant further study, which will include laboratory analysis of water/rock interactions using local alluvium and the local CBM water. The preliminary data from these two sites indicate that groundwater degradation may be greater in off-channel sites like that of Coal Creek as opposed to in-channel sites like Beaver Creek. Interpretations of these measurements could potentially explain the flow of infiltrating water, the causes of changes in water quality, and can help determine the best course of action regarding water disposal in CBM mining.

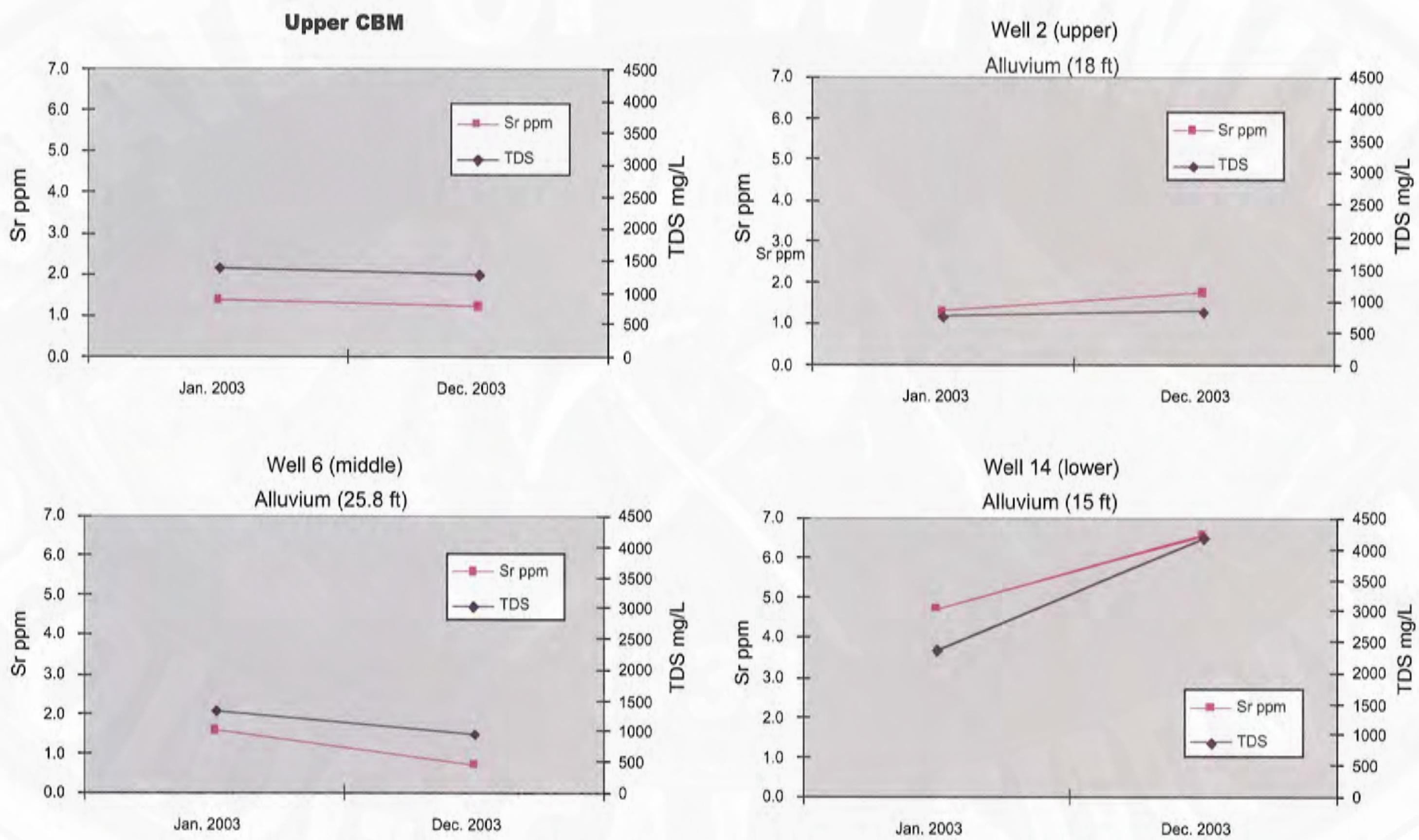


Figure 6. Beaver Creek, strontium concentration and TDS changes with time.

Session 2: Well Completion, Monitoring, and Produced Water Treatment—Wyoming Union, Yellowstone Ballroom

Co-Chairs: Dennis Lamb, Wyoming Department of Environmental Quality and KJ Reddy, University of Wyoming

Editor's Note:	*Titles of presentations shown on this page may be somewhat different from the written articles published in this volume*
8:00 a.m.	Wellbore completion methods for coalbed methane wells in the Powder River Basin I: Implications for water and gas production–Lourdes B. Colmenares, Stanford University; Mark D. Zoback, Stanford University
8:20 a.m.	Wellbore completion methods for coalbed methane wells in the Powder River Basin II: Toward optimal completion practices–Mark D. Zoback, Stanford University; Lourdes B. Colmenares, Stanford University
8:40 a.m.	Planning coalbed natural gas (CBNG) developments and maximizing gas production with the Downhole Raman Tool (DRT)–Rick Cox, WellDog, Inc.; John Pope, WellDog, Inc.
9:00 a.m.	Unconventional drilling methods for unconventional reservoirs–Doug Wight, CDX Gas, LLC
9:20 a.m.	Time-lapse monitoring of coalbed methane production: A case study from the Powder River Basin–Jerry M. Harris, Stanford University; Martins Akintunde, Stanford University
9:40 a.m.	Monitoring biological, physical, and chemical integrity of streams and implications for development of coalbed natural gas–Carol Endicott, Confluence Consulting, Inc.
10:00 a.m.	BREAK
10:30 a.m.	Coalbed methane produced water: Management options for sustainable development–James R. Kuipers, Kuipers and Associates; Kimberley MacHardy, Kuipers and Associates; Walter Merschant, Scientific Geochemical Services; Tom Meyers, Private Consultant
10:50 a.m.	Dispelling CBNG production water myths and using SO_2/sulfurous acid generators/sulphur burners–Terry R. Gong, Harmon Systems International, LLC
11:10 a.m.	Trip, tricks, and traps of using sulphur burners for treating CBNG discharge water prior to irrigation application–Neal E. Fehringer, Fehringer Agricultural Consulting
11:30 a.m.	Counter current ion exchange applied to sar modification in cbm produced water in the Powder River Basin, Wyoming–Douglas Beagle, Emit Technologies
11:50 a.m.	Re-injection of CBNG-produced water: Thinking small–Joel Adams, HydroSolutions, Inc.; Tom Osborne, HydroSolutions, Inc.

Wellbore completion methods for coalbed methane (CBM) wells in the Powder River Basin I: implications for water and gas production

Lourdes B. Colmenares and Mark D. Zoback–Department of Geophysics, Stanford University, Stanford, California

Well completion in the Powder River Basin

The shallow depth and relatively low cost of CBM wells in the Powder River Basin (PRB) has resulted in widespread use of open-hole/single horizon well completion procedures. A common completion technique used by many operators in the PRB is to drill to the top of the coal seam, case and cement the wellbore, then drill the coal section. After drilling, the coal section is under-reamed to enlarge the hole and minimize the effects of any formation damage. In many cases, water is then pumped into the wellbore to "clean it out" and "enhance" production. This procedure is called water-enhancement. Through analyzing the pressure and flow rate data during these operations, it is clear that these activities result in hydraulic fracturing of the coal. If vertical fractures extend up into adjacent strata, it could result in both excess CBM water production and inefficient depressurization of coals. To determine whether vertical hydraulic fracture growth might extend into adjacent formations, we have analyzed water-enhancement test data from about 550 wells to obtain the magnitude of the least principal stress (S_3) in the coal seams. In addition, we have also analyzed the relationship between hydraulic fracture orientation and water and gas production.

Hydraulic fracturing in the PRB

Water-enhancement test data shows that large volumes of water are pumped into the coal at constant pressure. This indicates the formation and propagation of a hydraulic fracture. Through analysis of data from over 500 wells in the PRB, we have confirmed that water enhancement activities result in hydraulic fracturing of the coal. The extent of a hydraulic fracture is controlled by the pumping pressure and the magnitude of the least principal stress with depth. A hydraulic fracture will always propagate perpendicular to the orientation of the least principal stress (S_3). Therefore, if S_3 corresponds to the minimum horizontal stress, this indicates that the hydraulic fracture propagates in a vertical plane. If the hydraulic fracture propagates vertically through the coal seam and through a confining unit, then the migration of groundwater toward the producing well could occur. If S_3 corresponds to the overburden stress, this indicates that the hydraulic fracture will propagate in the horizontal plane.

Various lines of evidence suggest that after a relatively short period of production (several months), an appreciable amount of the water produced from CBM wells may come from the formations adjacent to the coal seams (personal communication with several operators, 2002 through 2003). It seems that one factor possibly exacerbating this is the vertical growth of hydraulic fractures during the drilling and completion of CBM wells.

Least Principal Stress (S_3) in the PRB

In **Figure 1** we show a water-enhancement test plot from the PRB. The upper and lower panels show the flow rate in gallons per minute (gpm) and barrels per minute (bbls/min) respectively. The middle panel shows the pressure-time history while the water was being pumped into the well. When a fracture is produced during the water-enhancement procedure, the pressure-time history from the water-enhancement test (middle panel in **Figure 1**) is similar to the pressure-time history of a Leak-off Test (**Figure 2**). Leak-off Tests are a common type of test in the oil industry that yields important information about the least principal stress. A hydraulic fracture has been formed if large volumes of water are pumped into the coal at constant pressure. In the ex-

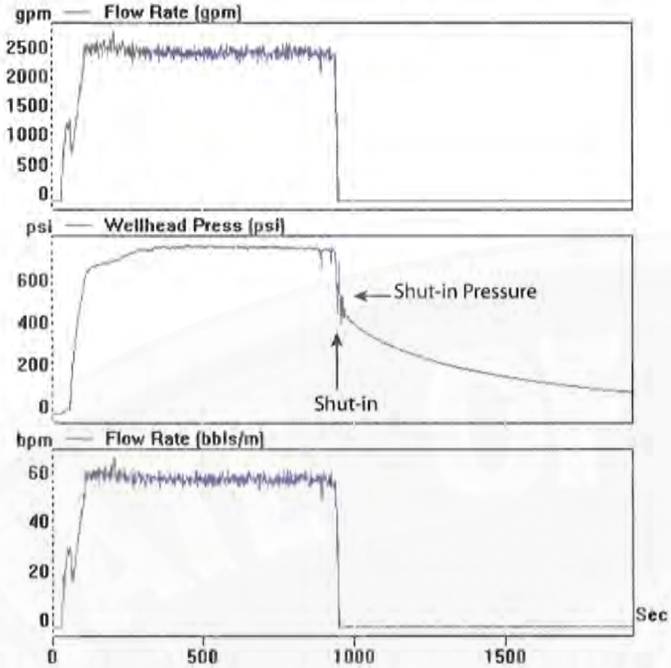


Figure 1. Water-enhancement test from a CBM well in the PRB.

ample we show in **Figure 1**, we can observe that at the surface, the Fracture Propagation Pressure (FPP) is 800 pounds per square inch (psi) and the Shut-in Pressure (SIP) is 600 psi. To determine the magnitude of the least principal stress at the depth of this test, it is necessary to add the pressure in the wellbore due to the column of wellbore fluid.

To date, we have obtained the magnitude of the least principal stress (S_3) for 372 wells. **Figure 3** shows the location of the analyzed data. Even though we have obtained results for different coal seams, we will only show here the analysis we performed for the Big George coal from Area D. In **Figure 4**, the black line is the overburden stress or S_v and the gray line corresponds to the hydrostatic pressure or P_{hyd} (0.44 psi per foot). All the wells located in T47N R74W and some wells located in T46N R74W (**Figure 4c**) show that the magnitude of the least principal stress corresponds to the overburden, that is, the fractures propagate horizontally (**Figure 4a**). All the wells located in T47N R75W and most of the wells located in T46N R74W (**Figure 4c**) indicate that the least principal stress corresponds to the minimum horizontal stress, that is, the fractures would be expected to propagate vertically (**Figure 4b**). It is important to note that the variation in magnitude of the least principal stress is observed throughout the basin, not only for the Big George coal but also for the other coal seams.

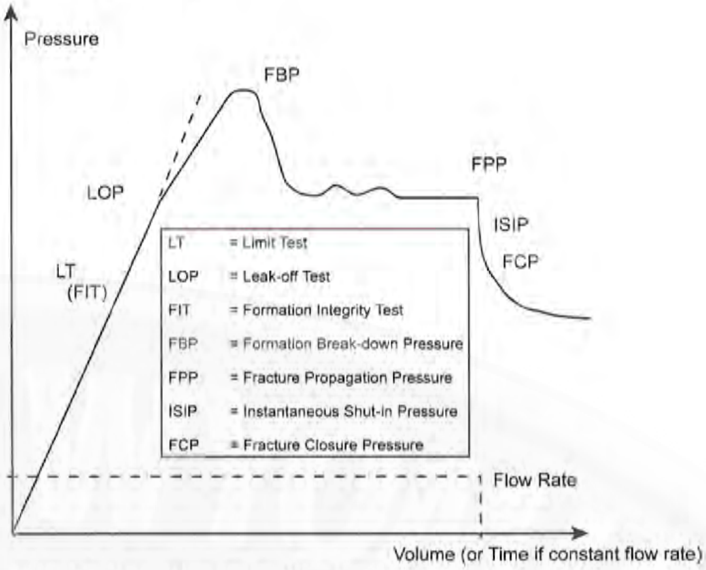


Figure 2. Schematic illustration of an extended Leak-off Test (Zoback et al., 2003).

Relationship between hydraulic fracture orientation and water and gas production for Area D

There is a marked differentiation in terms of water and gas production according to the type of hydraulic fracture formed in the Big George coal. All the water and gas production data were obtained from the Wyoming Oil and Gas Conservation Commission (WOGCC) website. As it can be seen in **Figures 5a** and **5b**, wells with vertical fractures produce more water than wells with horizontal fractures. In fact, 71% of the CBM water from the Big George coal is produced by only 32% of the wells, all of which are characterized by vertically propagating hydraulic fractures. These wells have been in production for at least 19 months and they are still not producing any gas. Actually, gas production only occurs in wells (with horizontal or vertical fractures) that have water production rates less than 10,000 barrels/month (**Figures 6a** and **6b**). Therefore, only 68% of the wells are gas producers.

In **Figure 7,** we present a plot of gas production versus water production from Big George coal not only for Area D but also for the central part of the basin. It shows again that wells with vertical fractures are the only ones producing very high volumes of water and at the same time, their gas production is either zero or non-existent. We can also see that for wells with low water production rates, the gas production is better for wells with vertical fractures than for wells with horizontal fractures.

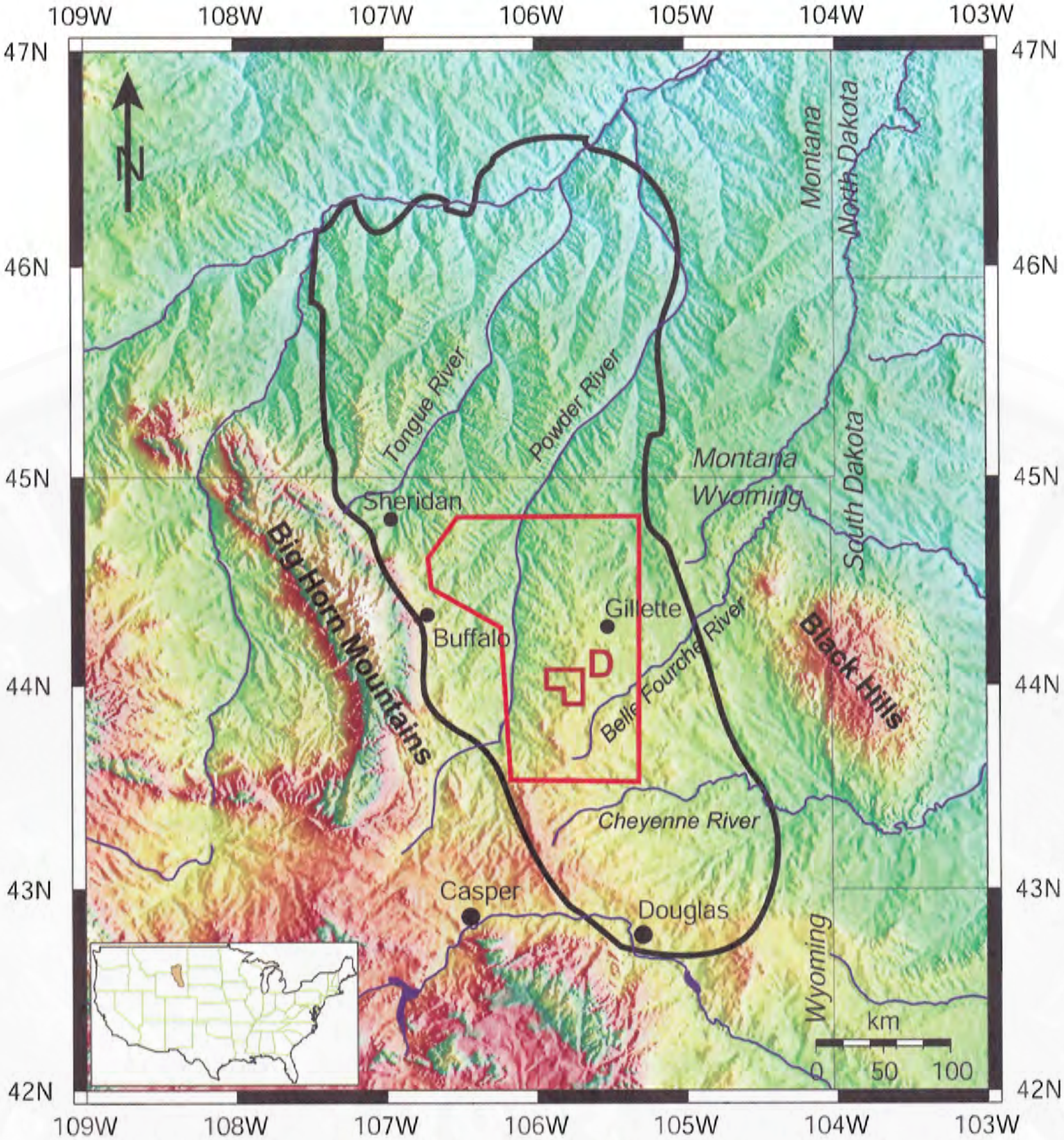
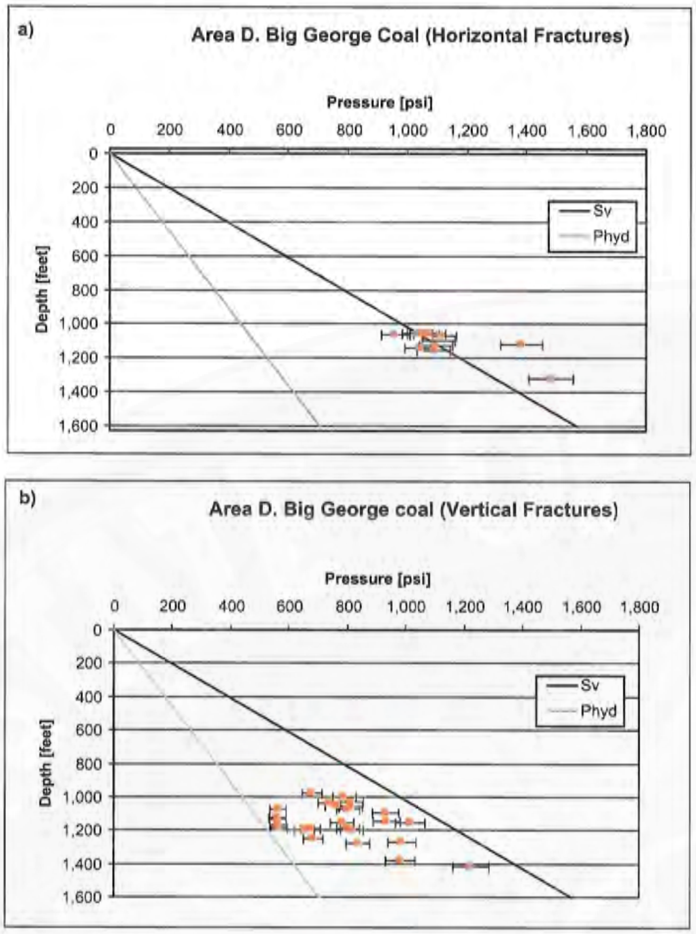


Figure 3. Water-enhancement test data from ~550 wells were obtained from the area delineated by a red line. The data from Figures 4, 5, and 6 come from Area D, delineated by a brown line.

Conclusions

Data on least principal stress has been compiled from 372 wells, which allows us to demonstrate that vertical hydraulic fracture propagation does occur in many places in the basin whereas the hydrofrac growth appears to be horizontal in other areas. Where the least principal stress is vertical, hydraulic fracture growth is horizontal and water production is minimal. Where the least principal stress is horizontal, fracture growth is vertical and water production is significantly greater for some wells. It is important to note that all of the wells with exceptionally high water production are always associated with vertical fracture growth. In these same wells, there are very significant delays in gas production, apparently due to inefficient depressurization of the coals. Approximately half of the wells characterized by vertical hydraulic fracturing are also characterized by very high water production in Area D. In general, wells with vertical fractures produce more gas than wells with horizontal fractures if their water production is low, that is, comparable to that of wells with horizontal fractures.



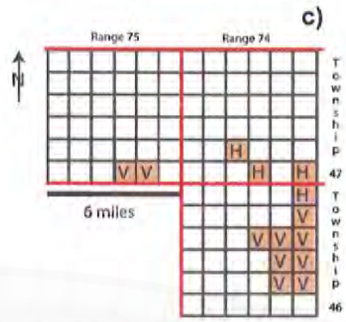
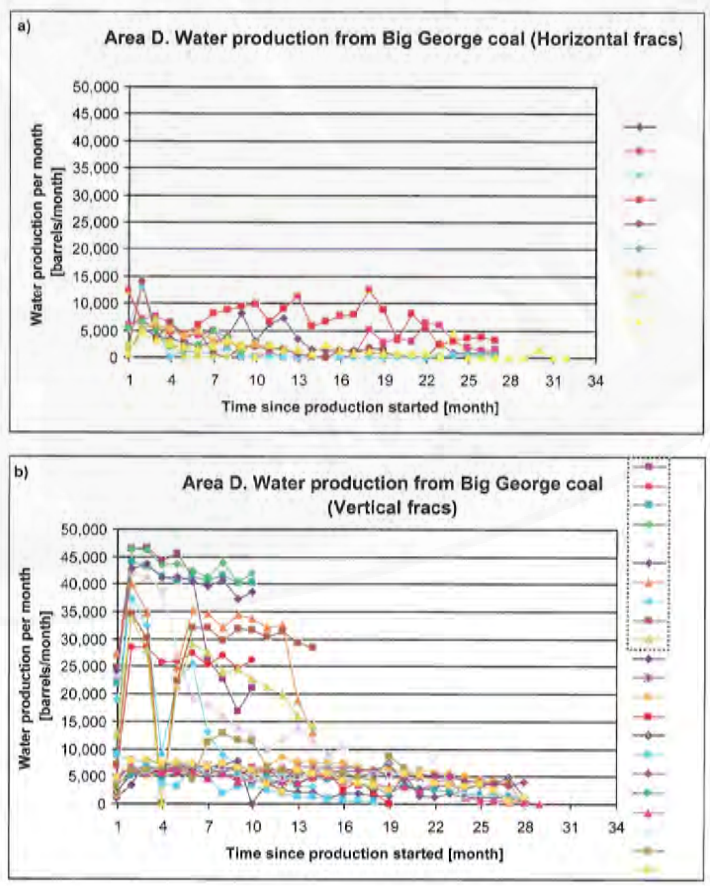


Figure 4. Magnitude of S_3 from the Big George coal in Area D versus depth. a) S_3 corresponds to the vertical stress, b) S_3 corresponds to the minimum horizontal stress and c) Occurrence of horizontal (H) and vertical (V) hydraulic fractures in Area D. The location of this area can be seen in Figure 3.

Figure 5 (below). Water production from wells in the Big George coal in Area D. There is a marked difference in water production between the wells that have a) horizontal fracture propagation and those that have b) vertical fracture propagation. The water production rate in the wells with vertical fractures is about 7 to 10 times larger than that of the wells with horizontal fractures. The blue dashed box encloses the wells with the highest water production rates.



Acknowledgements

Thanks to Conoco-Phillips, Marathon Oil-Pennaco Energy, Williams, and Wolverine Energy for kindly providing the data used in this study. This work was made under the auspices of the Western Resources Project (WRP).

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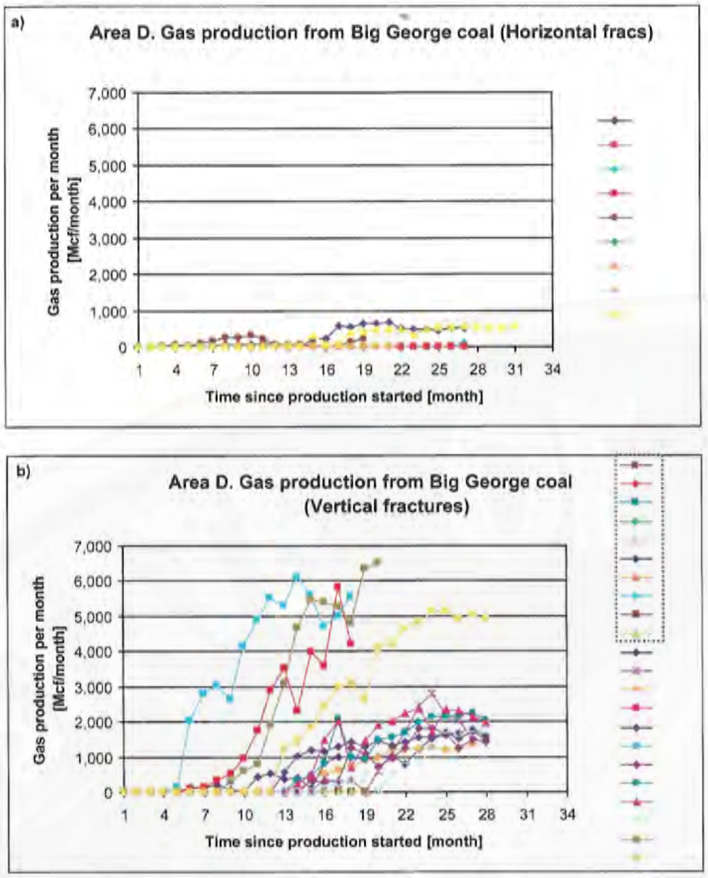

Figure 6. Gas production from wells in the Big George coal in Area D. a) Gas production from wells with horizontal fractures is immediate but very low. b) All the wells producing more than 10,000 barrels/month of water, have not produced any gas even though they have been in production for 19 months already (wells enclosed by dashed blue line, see also Figure 5b). For the wells with vertical fractures, gas production comes only from wells producing less than 10,000 barrels per month of water and it should be noted that the gas production is not immediate; however, in these wells gas production is better than for wells with horizontal fractures.

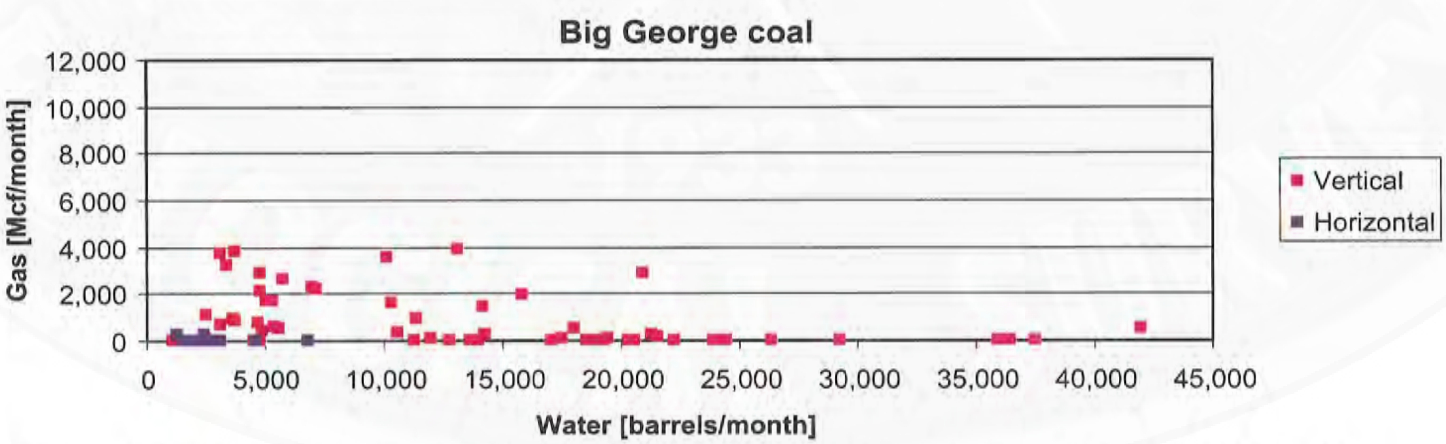

Figure 7. Gas production versus water production for Big George coal in the central part of the basin. Each data point represents a well. Red squares symbolize wells with vertical hydraulic fractures and blue squares symbolize wells with horizontal fractures.

Wellbore completion methods for coalbed methane (CBM) wells in the Powder River Basin II: Toward optimal completion practices

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Summary of findings

In our companion study (Colmenares and Zoback, 2005, this volume, pages 37-41) we demonstrated:

i. Water-enhancement activities during wellbore completion results in hydraulic fracturing of the coal,

ii. All of the wells with exceptionally high water production are associated with vertical fracture propagation,

iii. In these same wells, there are very significant delays in gas production, apparently due to inefficient depressurization of the coals,

iv. Approximately half of the wells characterized by vertical hydraulic fracturing are also characterized by excessive water production.

In light of this, we recommend the following:

i. In areas of known vertical fracture propagation, it is necessary to limit the injection during the water enhancement tests.

ii. In areas of unknown least principal stress, water-enhancement procedures should be carried out in two steps:

   a. A minifrac (~2 bpm for ~2 min) should be done to determine the magnitude of the least principal stress and thus whether fracture propagation would be vertical or horizontal.

   b. If the least principal stress is found to correspond to the overburden (approximately 1 psi per foot), it is safe to assume that horizontal fracture propagation occurs and the water enhancement activities can proceed at whatever rate and duration the operator chooses. If the least principal stress corresponds to the least horizontal stress (i.e. vertical fractures will occur), the injection during water enhancement should be limited.

Water-enhancement tests, least principal stress, and hydraulic fracturing

The data show that large volumes of water are pumped into the coal at constant pressure, which indicates the formation of a hydraulic fracture and its propagation. It is important to note that the wells characterized by vertical fracture growth were subjected to essentially similar water enhancement activities during completion: water was pumped into the wells at a rate of about 60 barrels per minute for approximately 15 to 20 minutes. From the water-enhancement tests, we have been able to determine the magnitude of the least principal stress for wells targeting different coals located throughout the basin. As the hydraulic fractures always propagate perpendicular to the direction of the least principal stress, after we determined whether the least principal stress was the overburden or the minimum horizontal stress (S_{hmin}), we were able to identify if the hydraulic fractures were propagating in the horizontal or the vertical plane, respectively. This has allowed us to map the occurrence of vertical and/or horizontal fractures in the central part of the basin to an extent, because even though we have obtained water-enhancement test data from about 550 wells, this only represents 4% of the total amount of wells in the Powder River Basin. Therefore, more data are needed to produce much more reliable maps.

As can be seen in **Figures 1**, **2**, and **3**, vertical and horizontal fractures occur in many areas of the basin. The blue color represents areas where the fractures are

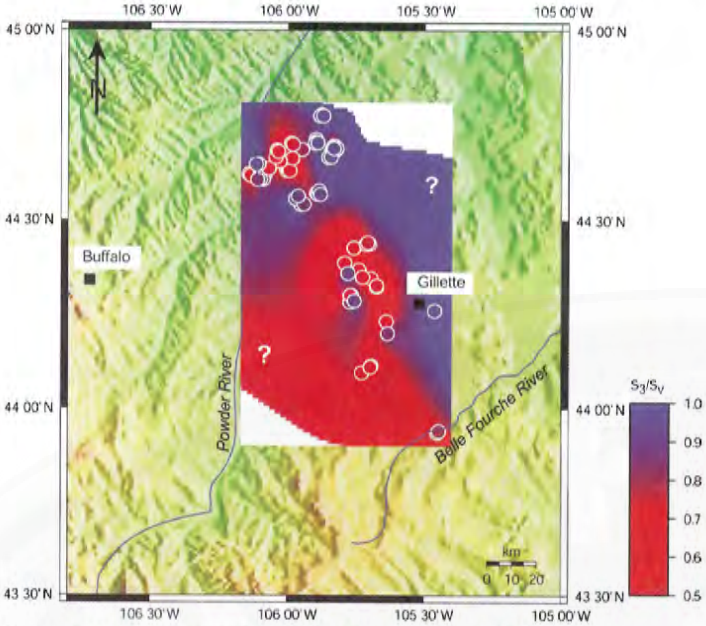

Figure 1. Map showing variation of S_3/S_v for the Anderson coal. The circles are actual data points. If $S_3/S_v = 1$, horizontal fractures are expected. If $S_3/S_v < 1$, vertical fractures are expected.

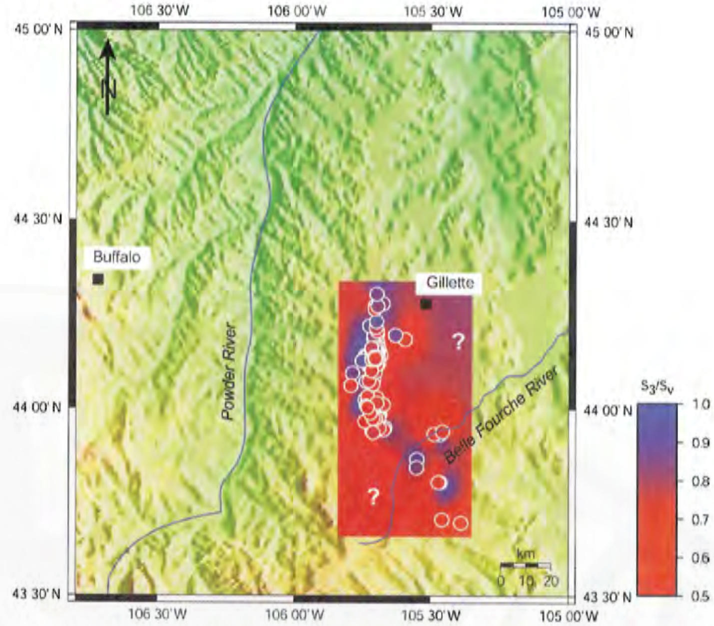

Figure 2. Map showing variation of S_3/S_v for the Wyodak coal. The circles are actual data points. If $S_3/S_v = 1$, horizontal fractures are expected. If $S_3/S_v < 1$, vertical fractures are expected.

horizontal, that is $S_3 = S_v$, therefore $S_3/S_v = 1$. The red shades represent areas where the fractures are vertical, that is $S_3 = S_{hmin}$, therefore $S_3/S_v < 1$. These maps were made using the interpolation algorithm of GMT, therefore the areas that do not contain individual points are areas where there is no control over the interpolation and the colors should be interpreted carefully (hence, the question marks in the figure). For Anderson, Big George, and Wyodak coals, these maps are quite useful for future developments in the basin as long as new wells are drilled in areas where there is existing data.

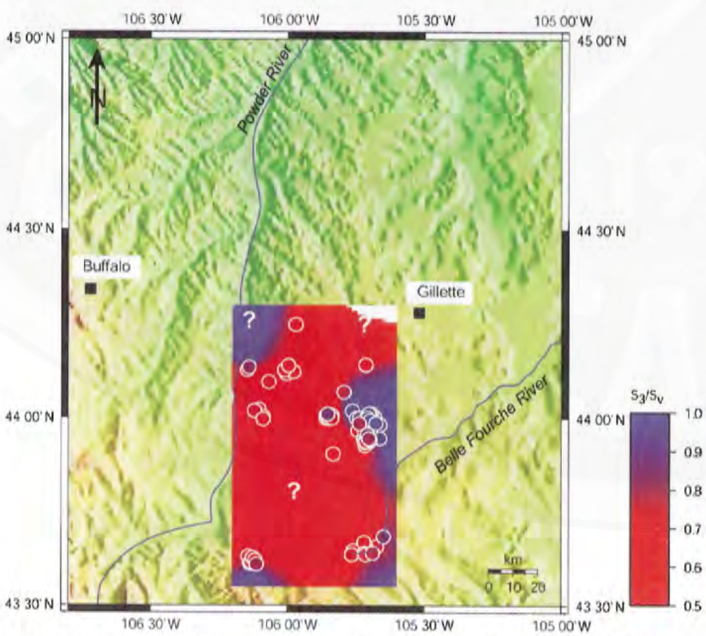

Figure 3. Map showing variation of S_3/S_v for the Big George coal. The circles are actual data points. If $S_3/S_v = 1$, horizontal fractures are expected. If $S_3/S_v < 1$, vertical fractures are expected.

In areas of vertical hydraulic fracturing: What is responsible for a large water production or a low water production?

One of the goals of this study is to understand the cause of such excessive water production in some wells while the water production is low for others in adjacent areas. We looked at four different factors: stratigraphy, thickness, depth, and initial water production.

Stratigraphy?

Excess CBM water production could result if vertical fractures extend up into adjacent strata, therefore creating a hydraulic connection between formations. We have analyzed the gamma ray logs for a few wells with vertical fractures in Area D. We were expecting to find that wells with vertical fractures and excessive water production were overlain by sand bodies, which behave as aquifers, and therefore could yield a great amount of water once the coals began to be dewatered. With respect to the wells with vertical fractures and low water production, we were expecting to find that the coals in these wells were overlain by shales, which have low permeability, and therefore do not yield water as sands do. Some of the wells with vertical fractures and large water production rates have sand bodies overlying the coal. However, other wells with vertical fractures and large water production rates have shales overlying the coal. Furthermore, we observed the same characteristics for wells with vertical fractures and low water production rates, that is, some are overlain by shales, but others are overlain by sands. More gamma ray logs will be analyzed to see whether a relationship does exist between vertical fracture growth and stratigraphy.

Thickness?

As can be seen in **Figure 4**, there is a general trend that the thicker coals in the Big George coal have greater water production. However, at a given thickness, for example 70 feet, the average water production of different wells ranges from 0 to 40,000 barrels per month. Therefore, a relationship could not be found. For the Wyodak coal (**Figure 5**), water production is generally low despite the thickness of the coal seam, that is, even when the coal is 100 or 180 feet thick, the average water production is less than 8000 barrels per month. Therefore, we can conclude that thickness might not be an indicator of the amount of water a coal will produce.

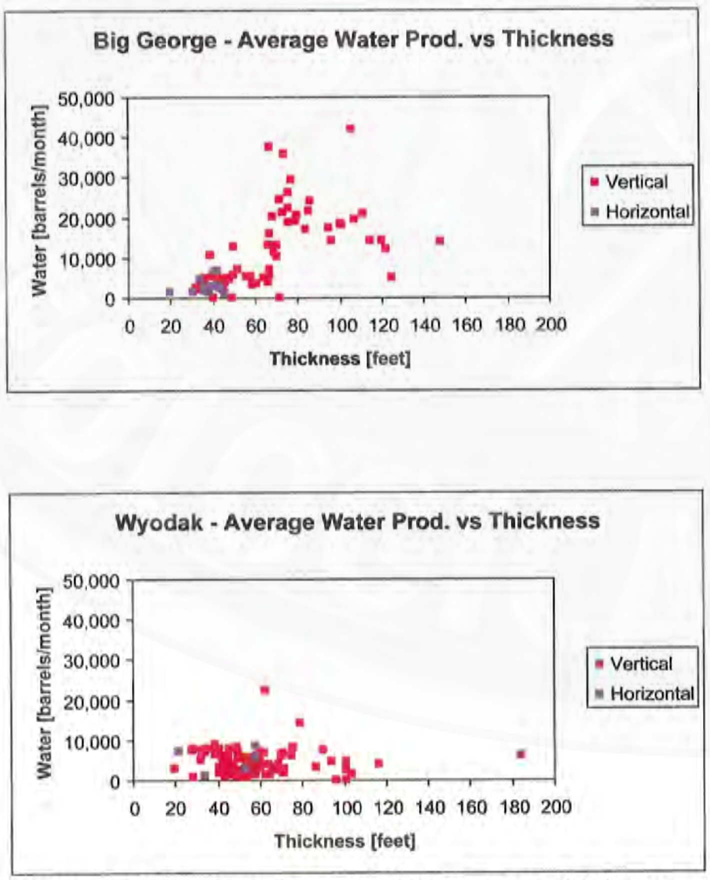

Figure 4. Average water production versus thickness for the Big George and the Wyodak coals. Red squares represent wells with vertical fractures and blue squares represent wells with horizontal fractures.

Depth?

Figure 6 shows that water production for the Big George coal is not related to the depth of the coal seam. Wells with vertical fractures and high water production rates can occur by targeting the same coal seam at an average depth of 750 feet as well as 1500 feet. Therefore, there is no direct correlation between the occurrence of vertical fractures and the depth of the coal.

Initial water production?

We also looked at initial water production rates to see whether this could give us a hint about the future water production, but as can be seen in **Figure 7**, there is no real trend between water or gas production and

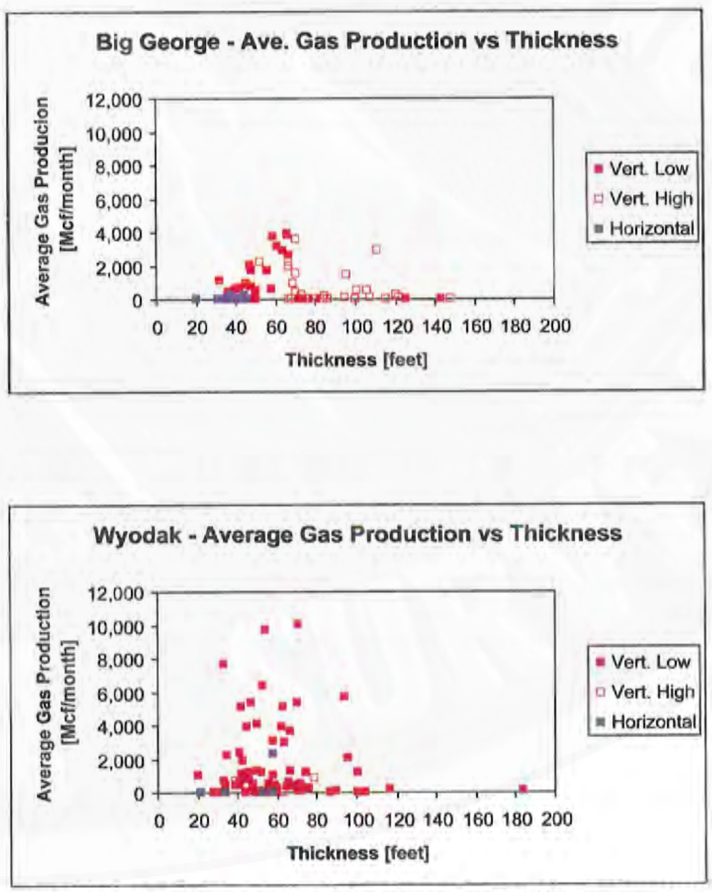

Figure 5. Average gas production versus thickness for the Big George and Wyodak coals. Red solid squares represent wells with vertical fractures and low water production rates. Red open squares represent wells with vertical fractures and high water production rates. Blue squares represent wells with horizontal fractures.

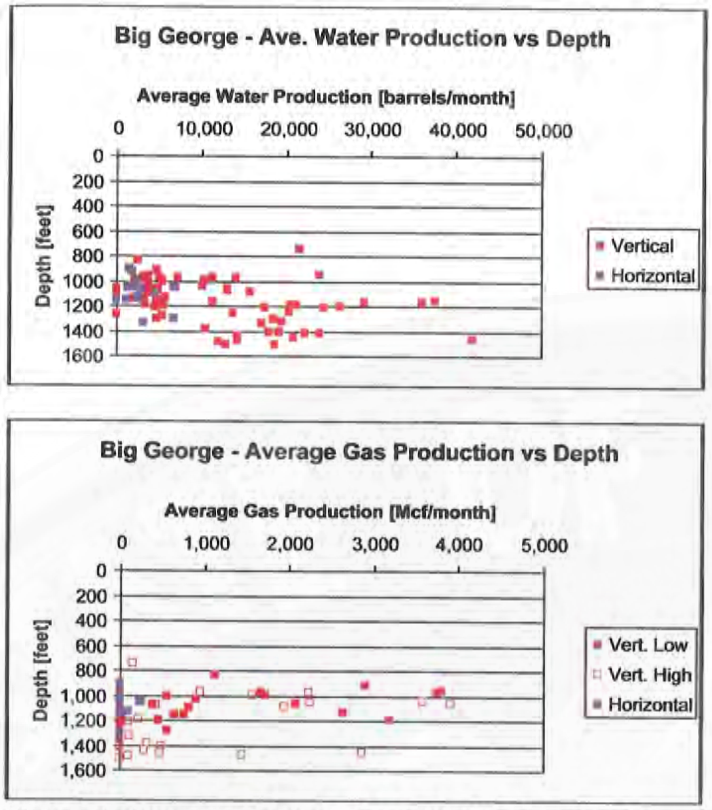

Figure 6. Average water and gas production versus depth for the Big George coal.

the initial water production. In these plots, the change in delta pore pressure (hydrostatic pressure minus observed pressure) is also presented. Well SRU2 shows a change of about 200 psi in delta pore pressure and it is still not producing any gas. Even though depressurization is implied, the large water production rate indicates that such depressurization might not be taking place effectively. Therefore, the coal at this site could be in connection with adjacent strata.

Recommendations

In areas of known vertical fracture propagation, it is necessary to limit the injection during the water enhancement tests. In areas of unknown least principal stress we suggest an alternative to the "standard" wellbore completion methods to limit the number of wells characterized by excessive water production and delayed gas. Water-enhancement procedures should be done in two steps. In the first step, a minifrac (~2 bpm for ~2 min) should be done to determine the magnitude of the least principal stress and thus whether fracture propagation would be vertical or horizontal. If the least principal stress corresponds to the overburden (approximately 1 psi per foot), it is safe to assume that horizontal fracture propagation occurs and the water enhancement activities can proceed at whatever rate and duration the

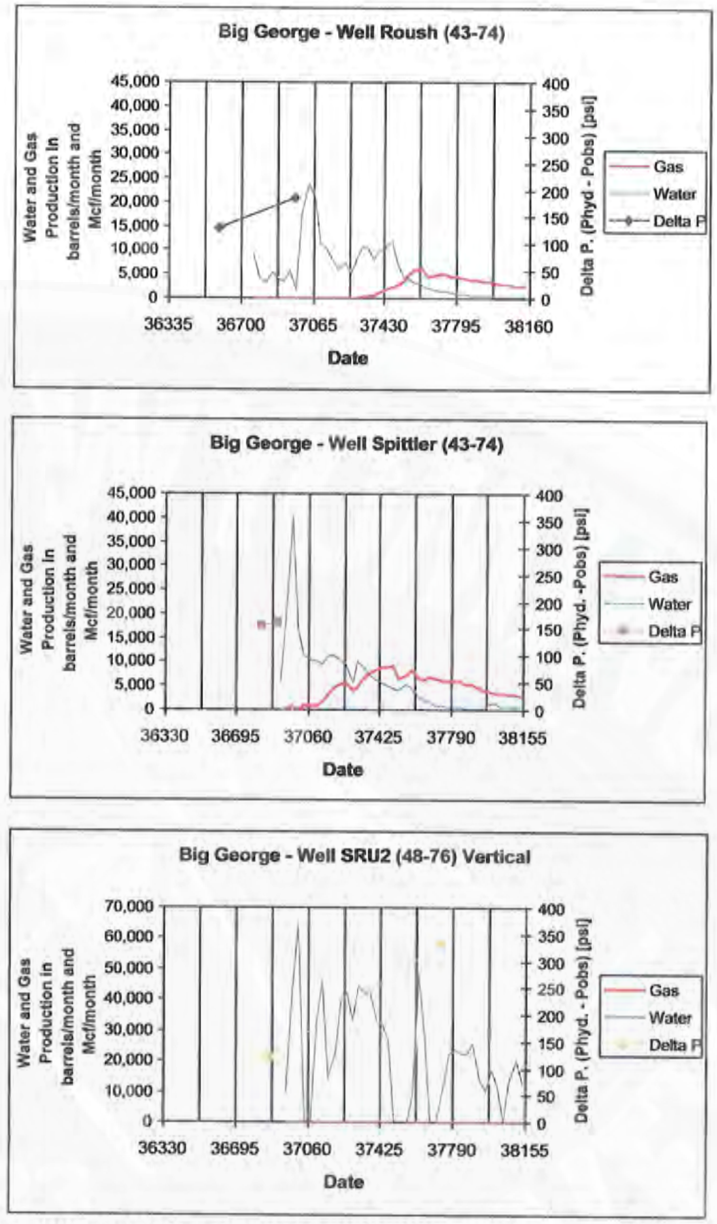

Figure 7. Water and gas production versus time since production started for the Big George coal. Observe that the initial water production for these wells is very similar (between 5000 to 9000 barrels in the first month), however their future gas production cannot be predicted from this only. Note that the production scale (barrels/month and Mcf/month) for wells Roush and Spittler is from 0 to 45,000, while for SRU2 the scale is 0 to 70,000.

operator chooses. Since many wells with horizontal fractures tend to be poor gas producers, such wells could be hydraulically fractured (and propped) to enhance gas production without risk of significantly affecting the rate of water production. If the shut-in pressure is significantly less than the overburden (~0.6 – 0.9 psi per foot), this implies that vertical hydraulic fracture growth will occur, and significantly reduced pumping is advised. This would be beneficial from the perspective of minimizing produced waters and decreasing the time for initial gas production.

Acknowledgements

Thanks to Conoco-Phillips, Marathon Oil-Pennaco Energy, Williams, and Wolverine Energy for kindly providing the data used in this study. Thanks also to Hannah Ross for helping with the analysis of the GR logs. This work was carried out under the auspices of the Western Resources Project (WRP).

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Planning coalbed natural gas (CBNG) developments and maximizing gas production with the Downhole Raman Tool (DRT)

Rick Cox and John Pope–WellDog, Inc., Laramie, Wyoming

CBNG producers need innovative technologies in order to reduce water production and maximize gas production during their development programs. In particular, they must understand how much gas is contained within a coal seam, which wells will produce quickly, and how to manage their resources based upon this information. WellDog is introducing new services for CBNG producers based on its proprietary Downhole Raman Tool (DRT). This technology is deployed as a testing service that allows producers to understand how to evaluate and develop their assets during early stages of CBNG development. The measurement is based upon an optical sensor packaged into a wireline tool format that measures methane concentrations in wellbore fluids, and in coal seams, under reservoir conditions. It also identifies and quantifies a variety of chemicals including hydrocarbons, fluids, rocks, salts, and gases. We will discuss the principles of Raman spectroscopy, the progression of a Raman spectrometer into an oil and gas logging tool, and our most recent commercial field results.

Special Report: Natural gas industry strategies—Horizontal drilling adds value in CBNG

Doug Wight, Vice President of Corporate Development–CDX Gas, LLC., Dallas, Texas

Commercial coalbed natural gas (CBNG) activity got its jump-start only 15 years ago in the United States, yet it already boasts impressive production and reserve rates. In fact, CBNG now represents 9 percent of the nation's total daily natural gas production and 25 percent of its natural gas reserve base.

Those numbers are impressive for a resource that did not even register on the exploration and production industry's radar screen only a short time ago. In fact, coalbed gas activity has seen such phenomenal growth, especially by independent oil and gas companies, that it is easy to forget exactly how young the CBNG industry is. Because the development of this unconventional resource is relatively new, the technology and methods for drilling and producing gas from coals is still largely in a state of progression, albeit a rapid progression.

While the first coal mining operation in the U.S. occurred in 1751 in Pennsylvania on Coal Hill (now Mount Washington), it took another 200 years for the first coalbed gas well to be drilled. Coal and natural gas (and oil) are often found together, and operations to develop one resource have been challenged by the presence of the other. For instance, coal has historically been a hindrance to drilling and producing oil and natural gas. For oil and gas producers, coal was something to be overcome, worked around, or worked through to reach the underlying hydrocarbon reserves. As natural gas began to emerge as a primary energy source in the U.S., it ultimately became evident that coals were a rich source of methane, not merely an obstacle to producing traditional natural gas reserves.

On the other hand, the coal mining industry long viewed the methane trapped in coal deposits as a nuisance. It was hazardous to miners, and venting or flaring it from mines was time-consuming, cumbersome, and environmentally undesirable. Although rural communities in the eastern U.S. have been fueling power projects with "gob gas" from coal beds for many years, little effort had historically been devoted to capturing the value of the gas generated during mining. However, the increasing relative worth of natural gas in recent years has caused the mining industry to rethink the value proposition of degasifying coals ahead of mining operations.

Viable resource

CBNG began to emerge as a viable resource three decades ago. However, there were no in-depth studies on the coal's gas content at that time. With firm evidence of substantial gas stores in coals, the U.S. Bureau of Mines began a scientific study in the 1970s to determine where and how much gas was stored in coal beds in the Black Warrior Basin in Alabama. That research revealed that gas contents of the coals could be sufficient to meet commercial production needs.

Test coalbed natural gas wells were drilled and completed in the 1970s and 80s in both the Black Warrior and San Juan basins, but the big CBNG boom did not occur until 1989, when Section 29 tax incentives for CBNG development were introduced. Those tax credits ended only three years later, and their end marked a sudden halt to significant development of new CBNG technologies and field activity. Good things did emerge from this short, quick growth spurt. For the most part, only fracture-stimulated wells had been tested and gained a foothold in both the Black Warrior and San Juan basins. As CBNG developers moved to other coal basins, it became clear that easy-to-produce Black Warrior and San Juan fields were not the norm. The industry was not yet prepared for the challenges it would face in the Rocky Mountains, Canada, and other western basins.

From this initial CBNG activity came a better understanding of the coalification process and gas stores in coals. Studies of the age of coals in relation to permeability taught the industry that immature coals are more permeable and that while more mature coals hold more gas, they are tighter and harder to produce. All this information enabled CBNG developers to be smarter about how and where they pursued projects, as well as the technology they used to drill and produce wells.

Most San Juan and Black Warrior wells drilled during the tax credit CBNG boom targeted high-permeability coals that were easy to produce with traditional vertical drilling and fracturing techniques. Starting in the late 1990s, production moved into the Powder River Basin in Wyoming, where coals also tend to be highly permeable and easy to produce with vertical wells. With the exception of these areas, vertical wells are often inefficient for coalbed natural gas production, requiring hundreds of wells to exploit a reservoir. Compounding that, vertically produced reservoirs take a long time to produce gas because they typically require a lengthy dewatering period to draw water from the coals and allow the gas to flow.

Horizontal CBNG drilling

Naturally, as the industry entered more challenging coal reservoirs like the Appalachian, Arkoma, Raton, and Piceance basins, interest in applying horizontal drilling gained ground. Although horizontal drilling costs can be at least double compared to a vertical drilling project, the technology has substantial benefits when implemented in CBNG. Traditional horizontal wells are best suited for highly fractured reservoirs that can create quick initial production returns. Drilling horizontal laterals increases the likelihood of intersecting a coalbed cleat or fracture at right angles to the dominant fracture direction. With laterals in the coal beds, the distance a gas molecule has to travel to the well is decreased and production time is minimized.

To be successful in a horizontal CBNG project, it is critical to intersect the fracture plane in the right orientation to maximize the number of fractures intersected. Fracture orientation studies provide some level of assurance in drilling fractures, but it is difficult to predict perfectly. Adding multiple laterals and under-balanced capabilities to horizontal CBNG drilling and completion maximizes the value of the technology in coalbed natural gas development by intersecting the fracture planes in the optimal orientations and minimizing formation damage to productive coal intervals.

Figure 1 shows an example of the Z-Pinnate™ advanced multilateral under-balanced drilling and completion system optimized for CBNG, incorporating a multilateral horizontal drainage network configured in a pinnate (the structural veins in a leaf) pattern. As shown in **Figure 2**, multiple pinnate patterns, or drainage networks, can be nested and drilled from a single well site to drain up to 1200 square acres of coal. This ensures significant and thorough fracture intersection while minimizing surface disruption.

By comparison, traditional vertical drilling and fracturing recovery methods require one well for every 80 acres of coal. Reservoir benefits aside, the ability to drain gas from 1200 acres of coal from one well site is a critical advantage, since many CBNG plays are located in areas where environmental sensitivities are high. The gross coal area drained by a single well location could become even larger in the future, with work now under-

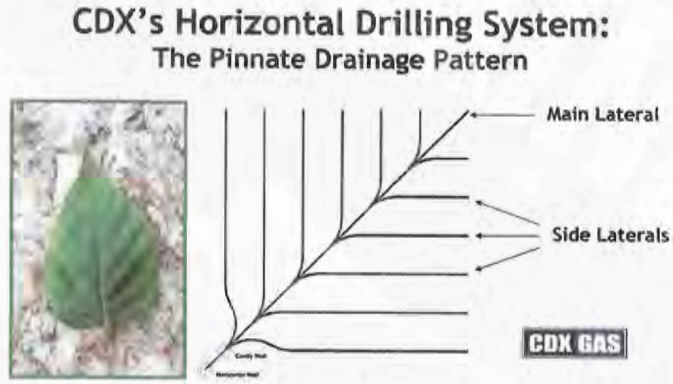


Figure 1. Example of single pinnate drilling system.

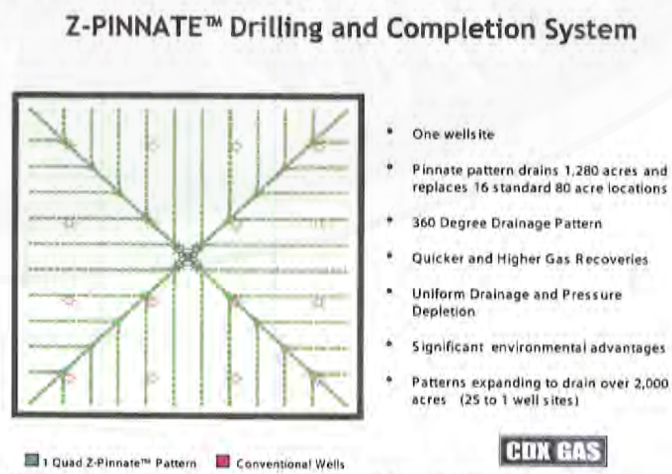


Figure 2. Example of quad pinnate drilling and completion system.

way to expand the effective drainage network from 1200 to 2000 acres from one well site.

The dual-well multilateral horizontal system provides efficient downhole water separation, allowing water to be easily pumped off. This creates ultra-low bottom-hole pressures, which in turn, enable high ultimate gas recoveries and low residual gas content at the time of mining. The dual-well system also allows for economical under-balanced drilling, as shown in **Figure 3**.

The combination of the leaf-shaped pinnate drainage network and dual-well under-balanced horizontal drilling enables the recovery of 80 to 90 percent of the CBNG in only 24 to 48 months, as illustrated in **Figure 4**. Of course, accelerated recovery rates provide significant economic benefits, and economies of scale are achieved when a single 1200-acre drainage network replaces 16 conventional vertical wells. Other benefits include minimal surface disruption, uniform drainage, increased safety in mining operations, and very low overall methane emission rates.

The key differentiating aspect of this technology is the under-balanced system. By intersecting the main well bore, an under-balanced environment is established. This minimizes, or even eliminates altogether, one of the principal obstacles to effective CBNG production: formation damage from mud weights. In conventional over-balanced drilling (i.e., the hydrostatic pressure of the mud column is greater than the internal pressure of the reservoir), even lighter-weight drilling muds can plug coal pores and fractures, thereby plugging off permeability and gas flow.

CDX's Dual Well System

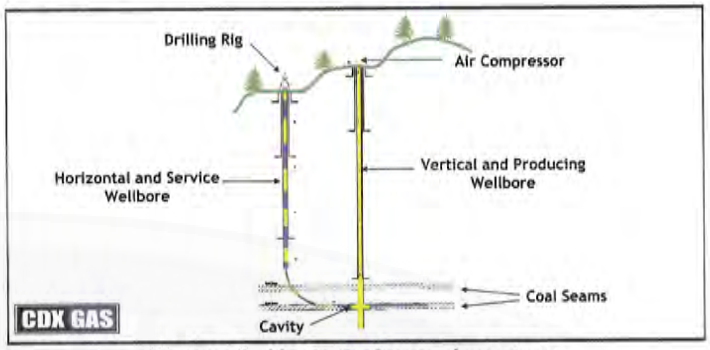
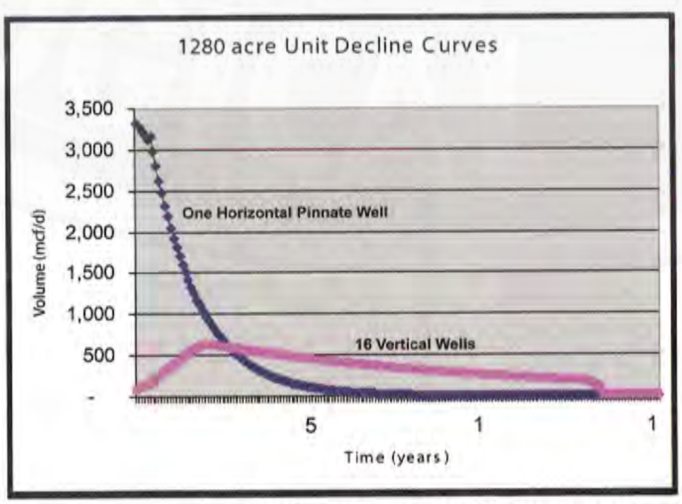


Figure 3. Underbalanced system.

The first application of the new CBNG drilling technology was at U.S. Steel Mining's (USM) Pinnacle Mine in southern West Virginia. USM had been using underground drilling techniques to pre-drain gas in advance of mining operations. Underground access constraints made it impossible to produce a sustainable gas supply, and the process required drain holes every 75 feet. Although methane was being adequately drained, costs were high because of the high-density underground drilling operations.

Horizontal drilling operations initiated from the surface appeared to offer significant benefits compared to underground drilling. Surface drilling operations can take place well in advance of mining. Similar to underground drilling operations, surface-initiated horizontal

Understanding the Production Profiles: *Rate versus Time Comparison*



CDX GAS

Figure 4. Cumulative rate versus time.

wells also offer higher ultimate recoveries than vertically drilled and fractured wells. Yet, problems relating to dewatering and cost remained.

Using the dual-well multilateral horizontal system, more than 20 billion cubic feet of methane gas has been recovered to date from the USM Pinnacle Mine alone. In fact, CDX Gas ranks as West Virginia's largest CBNG producer, with production of more than 14,000 million cubic feet of gas per day.

Against a backdrop of general supply tightness in the North American gas marketplace and higher commodity prices, domestic oil and gas operators are increasingly turning to unconventional resources like CBNG to secure new gas supplies. Total North American coalbed natural gas reserves are projected to increase to 7.5 trillion cubic feet (TCF) within the next few years, up from 4.5 TCF in 1998, making coalbed natural gas the fastest-growing source of natural gas.

The technology for producing the nation's valuable CBNG resource has come a long way in a short time, but greater things are yet to come as pilot projects spread to new coal-rich areas and development projects in basins all across North America gain momentum. As coalbed gas field activity proliferates, the technology for drilling, completing, and producing CBNG wells will continue to evolve. It will be interesting to see what other new technologies emerge for tapping CBNG and other gas-rich unconventional reservoirs.

Time-lapse seismic monitoring of coalbed methane production: A case study from the Powder River Basin

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Abstract

The objectives of this study are to characterize the coalbed methane (CBM) reservoir and monitor time-variant changes in the velocity of seismic waves associated with dewatering during CBM production. Dewatering causes a decrease in pore pressure resulting in an increase in gas saturation. Gas lowers the velocity of seismic waves whereas a decrease in pore pressure increases the velocity. Knowledge of the spatial distribution of gas between wells may be helpful in identifying both the source of produced water and the spatial efficiency of the dewatering process. This study is based on three time-lapse cross-well seismic surveys executed at a test site within the Big George Formation of the Powder River Basin (PRB). From the time-lapse surveys, we estimate that the spatial distribution of the velocity changes approximates 5 to 6% above the coal as well as inside the coal layer. This difference we believe, is due partly to changes in fluid saturation (from water to gas) and partly to changes in pore pressure occasioned by the dewatering process both within and above the coal. The observed changes demonstrate feasibility to monitor the CBM production process and that the changes are consistent with theoretically derived coal and rock physics models.

Introduction

The PRB accounts for about 800 billion tons of coal and is estimated to produce 25 trillion cubic feet of gas–about 20% of the CBM being produced in the U.S. Located in the central part of the PRB of Wyoming and Montana, the Big George is currently one of the world's most established fields. Along with the Wyodak, the Big George is a CBM producer at the PRB. Powder River Basin coals are biogenic, permeable, shallow, and low-rank coals. They are characterized by higher moisture content and lower carbon content when compared with high-rank bituminous coals. The common practice for primary CBM production at the PRB is to depressurize the coal, usually by pumping water out of the reservoir for several months. At the initial stage of dewatering, gas production is negligible, but increases and stabilizes as dewatering progresses over an appreciable period. Richardson and Lawton (2002) showed that the dewatering process affects the acoustic and elastic properties of the CBM reservoir, causing appreciable acoustic impedance discontinuity within the coal-bearing layer and the surrounding strata. These changes in turn affect the amplitude and travel times of reflected and transmitted waves, paving the way for cross-well seismic mapping of changes caused by the dewatering process.

In this study, cross-well seismic surveys were designed to image production-induced changes in P-wave velocity associated with primary CBM production at a site in the vicinity of the Big George Formation at the PRB. Geologically, the PRB is a thick sequence of sedimentary rock formed in a large down warp within the Precambrian Basement. Sediments range from Paleozoic at the bottom through Mesozoic to Tertiary at the top. Details about the basin's geology are contained in Larson (1989), De Bruin and others (2000), Randall (1991), and Rice and others (2000).

Cross-well seismic data acquisition

The cross-well seismic surveys were run between a pair of monitoring wells that straddle a completed CBM production well. The monitoring wells were provided for our surveys with the help of Conoco Philips, the U.S. Bureau of Land Management, and the Western Resources Project (WRP). The baseline survey was acquired shortly after the production well was completed and before dewatering began in December 2002, the first and second monitoring surveys were run in July 2003 and June 2004 respectively. Each of the surveys covered about 900 feet to the total depth of the well at about 1400 feet. Changes in the P-wave travel times can be seen in unprocessed seismograms though tomography was used to image the velocity changes between wells from the differences in travel times.

Data processing

A zero-offset gather from the data (**Figure 1**) provides useful stratigraphic information. The coal has a lower seismic velocity (~ 7500 feet per second) and is easily delineated (1150 to 1235 feet) by its larger travel time relative to surrounding zones. Strong tube waves are present in the data, though not easily seen in this gather. We pre-processed the data to suppress the tube waves and conditioned the direct arrivals for travel time picking of the P-wave first arrivals. We manually picked about 21,000 seismic traces from each data set and processed them with travel time tomography to produce the velocity image between wells (Harris and others, 1990 and Zhang and Toksoz, 1998). The resulting 2-D tomograms for the baseline and repeat surveys are shown in **Figures 2** and **3.** The baseline and repeat tomograms exhibit the same geologic characteristics (**Figure 3**) and provide images of the vertical and lateral changes in velocity. To permit quantitative estimation of changes in P-wave velocity due to CBM production, we computed the differences between the baseline and repeat tomograms and obtained the results shown in **Figure 4**.

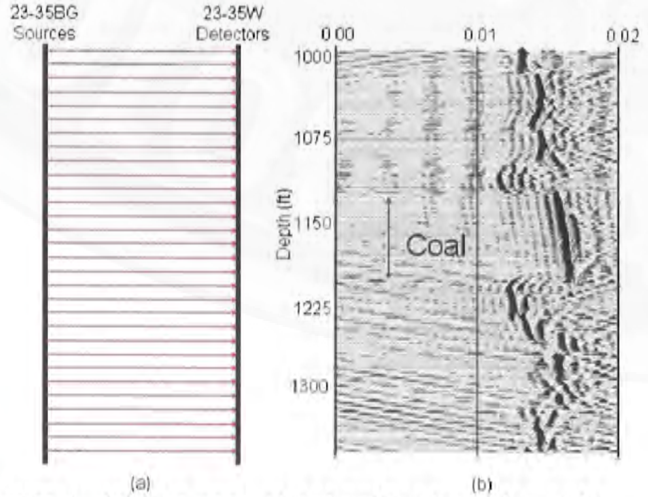

Figure 1. (a) The zero-offset gather includes only sources and detectors at the same depth. (b) The coal zone (1150'-1240') is clearly delineated by its low velocity, i.e., higher travel time.

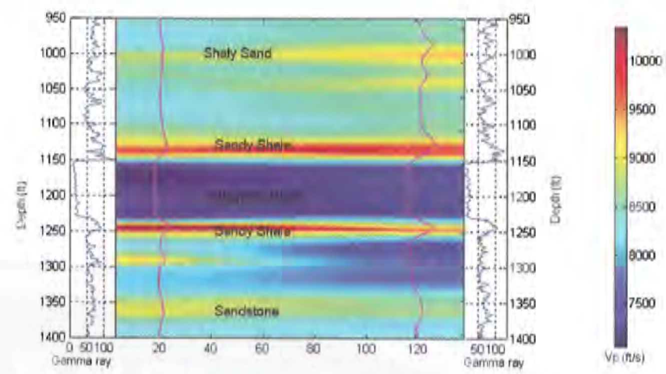

Figure 2. Baseline tomogram with gamma ray logs (insets are tomogram-derived velocity logs).

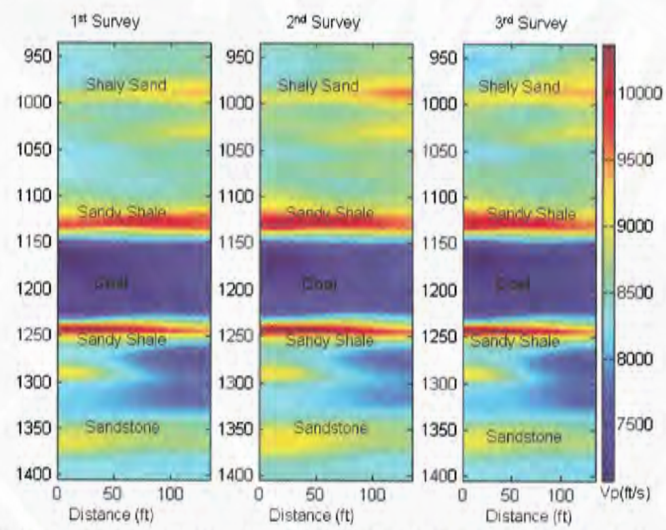

Figure 3. Baseline (first survey) and repeat (second and third surveys) tomograms.

Data interpretation and conclusions

Four distinct geologic units can be identified from the baseline tomogram. They include shaly-sand, sandy-shale, coal, and sandstone. Of interest to us is the low-velocity, biogenic and low-rank Big George coal zone at a depth of around 1150 to 1240 feet. Qualitative interpretation of the gamma ray logs plotted alongside the baseline tomogram (**Figure 2**) shows geological features similar to the ones observed on the baseline and repeat tomograms (**Figure 3**). This good correlation corroborates the quality of the tomographic inversion process. Analysis of the difference tomograms (**Figure 4**) shows that the P-wave velocity initially decreases by about 4 to 6% (first difference tomogram) within the coal zone due to partial gas saturation or methane desorption and later increases by about 5% (2nd and 3rd difference tomograms) due to continued depressurization and subsequent increases in differential pressure. Because

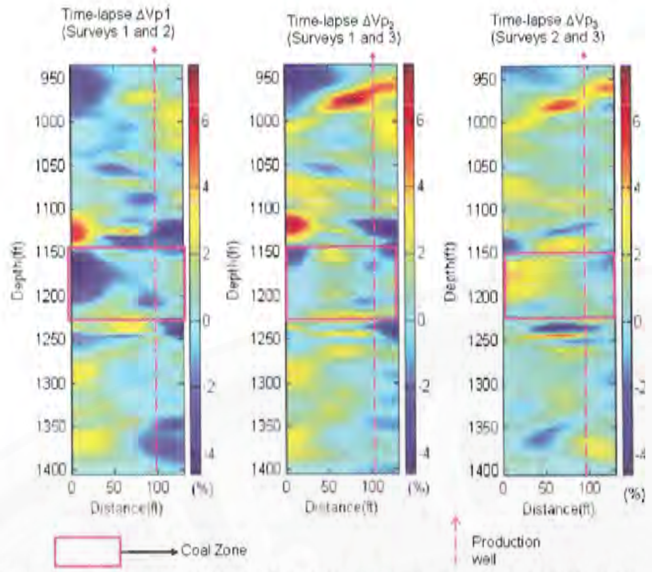

Figure 4. Measured difference tomograms from the time-lapse surveys (from left to right: first difference tomogram, second difference tomogram, and third difference tomogram).

these changes are so small, there is also some possibility for inversion artifacts in the difference tomograms. There are also changes both above and below the coal zone. These changes might be due to pressure-related anomalies and fluid drainage and/or migration through hydraulically active fractures (Colmenares and Zoback, 2003) to surrounding porous and permeable beds. The observed time-lapse changes agree reasonably well with predictions based on Gassmann (1951) (**Figures 5** and **6**), underscoring the effectiveness and applicability of high resolution cross-well seismic for monitoring.

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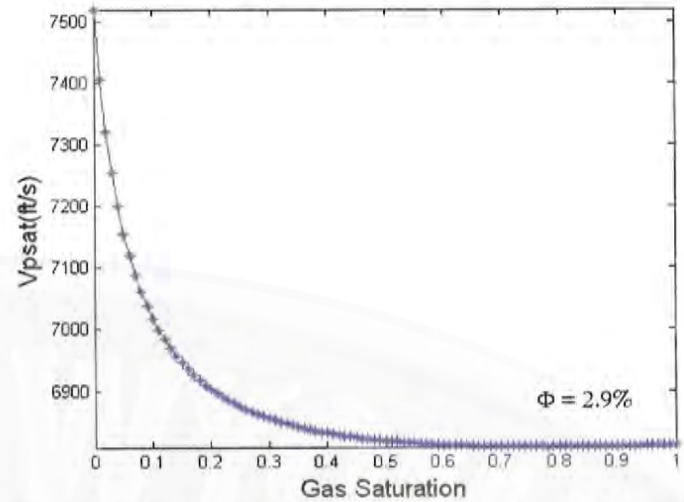

Figure 5. Velocity in saturated coal as a function of gas saturation. Fully water saturated velocity at around 7500ft/s drops to around 6900ft/s due to gas saturation (remodeled data from Yu and others, 1993).

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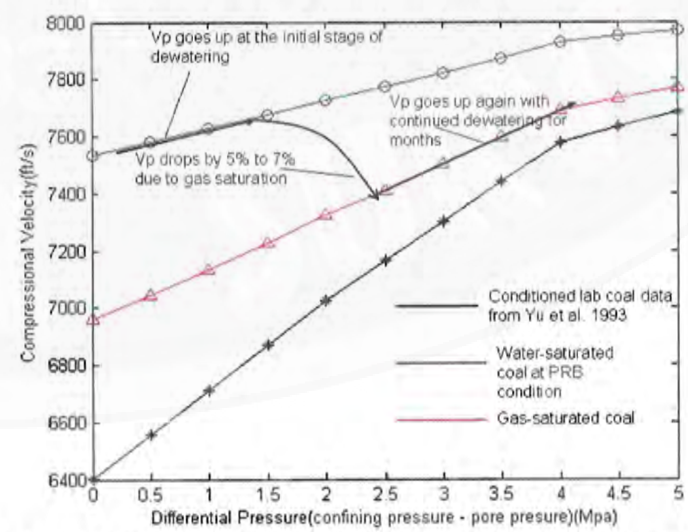

Figure 6. P-wave velocity's behavior in saturated coal as a function of differential pressure (modeled using Gasmann's equation and data from Yu and others, 1993).

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Monitoring the biological, physical, and chemical integrity of prairie streams: Implications for the sustainable development of coalbed natural gas

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The explicit objective of the Clean Water Act of 1972 is to "restore and maintain the chemical, physical, and biological integrity of the nation's waters." This objective has implications for coalbed natural gas development as associated activities, such as wastewater management and depletion of aquifers, have unknown potential to affect the integrity of surface waters. Uncertainty regarding the possible effects of this industry necessitates an adaptive management approach, which includes a strong monitoring component and an understanding of ecology of the surface waters in the region.

There are several challenges in evaluating the integrity of prairie streams. For example, a lack of scientific scrutiny compared to cold-water streams means there is often a scarcity of baseline data and fewer tools available to evaluate the integrity of these waters. In addition, considerable natural variability in physical and chemical conditions presents a challenge in attributing observed conditions to natural disturbance or human activities. Moreover, common methods developed for evaluation of the integrity of streams have limitations for application in prairie systems. The challenge to resource managers is to develop the necessary tools and knowledge in face of the rapid pace of methane development.

The objective of this paper is to present an approach to evaluating the integrity of prairie streams while describing the associated challenges using an investigation on the Powder River in Wyoming as the example (Confluence, 2004). These evaluations include assessment of three biological assemblages, key water quality parameters, and numerous measures of the physical and vegetative setting. In an adaptive management framework, such monitoring results provide a screening tool, which should trigger appropriate actions such as changes in wastewater management or additional investigations when indicated.

An understanding of the factors that shape the ecology and, therefore the potential biological, physical, and chemical integrity of prairie streams, is a critical component of their evaluation and management. A combination of characteristics including geology, hydrology, climate, fluvial geomorphology, and vegetative features influence these waters. Together, these components promote streams with fine-grained bed materials, high turbidity, moderate salinity, fluctuating flows with periods of intermittency, and warm summer temperatures. Consequently, intact and balanced assemblages of fish, macroinvertebrates, and periphyton adapted to these conditions constitute a high degree of biological integrity in prairie streams. Nevertheless, it is important to acknowledge that these are harsh environments where even these highly adapted organisms are living on the ecological edge (Dodds and others, 2004). Therefore, human disturbances that exacerbate already severe conditions may tip the balance away from support of these beneficial uses. For example, activities that decrease recruitment of large woody debris from cottonwood galleries may limit refugia for fish during periods of stream intermittency. Sustainable development of coalbed methane means avoiding or mitigating the potential effects of human activities on chronically stressed communities.

Evaluation of fish community composition is a common approach to assess the biological integrity of streams. Recent research in prairie streams in Montana (Bramblett and others, 2003) provides an index of biotic integrity (IBI) for fish, although several factors limit its applicability in the Powder River. The size of the Powder River watershed is one constraint, as most streams used in the development of the index had considerably smaller drainage areas. Another limitation is the vulnerability of several species of fish to sampling gears. The Environmental Protection Agency's Environmental Monitoring and Assessment Program (EMAP) methodologies used in the development of the IBI and this investigation call for the use of one collecting gear, in this case seines. However, other researchers have found several species relatively invulnerable to seining (Patton and others, 1998a). Therefore, future investigations on the Powder River should deploy additional sampling gears such as hoop nets set overnight. Moreover, development of an IBI for riverine environments would be a valuable tool in the management of this river.

Although fish communities in the Powder River scored relatively low on the IBI, there were numerous indications of a high degree of biological integrity in the Powder River based on its fish assemblage. Fish were relatively abundant with 19 species captured. Native species dominated the samples, including several species declining in Wyoming due to various human disturbances including flathead chub (*Platygobio gracilis*) and channel catfish (*Ictalurus punctatus*) (Patton and others, 1998b). Other pertinent findings included identification of important rearing area for channel catfish downstream of significant discharge of coalbed methane produced waters. Fisheries managers and permitting agencies need to identify, monitor, and protect these critical areas and sensitive species.

Several species of fish known to exist in the Powder River were absent or rare in samples. Sauger (*Sanders canadense*), a species declining throughout its range (McMahon, 1999), was not captured; however, this may have been a function of its relative invulnerability to seines. In contrast, the sturgeon chub, a species of special concern and former candidate for the endangered species list, was present at only one location with just two individuals sampled. This differs from previous investigations that found sturgeon chub throughout the Wyoming portions of the Powder River (Patton and others, 1998a; USFWS, 1993). In an adaptive management approach, these results should trigger additional investigations into the status of these sensitive species in the Powder River.

EMAP methods employed to sample macroinvertebrates in the Powder River were not effective in this system. The EMAP methods involve systematic sampling of small areas of streambed at regular intervals. However, monotonous sand substrate combined with marked fluctuations in the extent of inundated streambed probably result in patchily distributed benthic organisms requiring a more targeted approach to sampling. Consequently, macroinvertebrates were rare in samples yielding low scores on the index of biological integrity for prairie streams (Bukantis, 1998). Paradoxically, the flathead chub, the most abundant fish in the Powder River, is a benthic invertivore indicating that macroinvertebrate populations are sufficiently productive to support an abundance of this species. Studies of trophic relations in the Powder River and development of more appropriate sampling strategies are important research needs in solving this paradox and developing an appropriate index of biotic integrity for macroinvertebrates.

EMAP methods for periphyton sampling also have limitations in evaluating the biological integrity in the Powder River. Similar to macroinvertebrates, great temporal variability in inundation and desiccation of streambed surfaces in the Powder River makes it difficult to target areas likely to support attached algae. Nevertheless, diatoms have applicability in evaluations of the effects of coalbed methane development due to their known tolerances to salts. Development of more targeted approaches to sampling periphyton would provide a valuable tool in monitoring the Powder River.

Physical and chemical water quality parameters indicated relatively high levels of salts at several locations in the Powder River compared to baseline data in the U.S. Geological Service database. Notably, sodium adsorption ratio (SAR) at a sampling station below significant coalbed methane discharges exceeded the maximum SAR measured in the Wyoming portions of the Powder River. In addition, some relatively toxic anions, chloride and sulfate, were elevated compared to baseline data at several sampling stations. Complications in drawing inferences from these data include the high variability of flows throughout the study. Concentrations of salts may vary with mobilization, concentration, and dilution depending on hydrographic factors. Nevertheless, these results should trigger evaluations of anthropogenic sources of salt loading to protect water quality and beneficial uses.

A significant finding in evaluations of stream morphology and vegetation was the role of vegetation in forming important habitat features. For much of the Wyoming reach of the Powder River, large woody debris from cottonwood trees was the sole pool-forming agent. Alarmingly, salt cedar (*Tamarisk sp.*) an exotic species, is encroaching in the Powder River, and is apparently supplanting cottonwood seedlings on many recent alluvial bar habitats. Salt cedar is considerably more tolerant of salts than cottonwoods (Hansen and others, 1995) but does not support the same ecological functions. Furthermore, it has high rates of evapotranspiration and can attenuate stream flows. The potential for salt cedar to outcompete cottonwoods has dire consequences for the integrity of the Powder River over the long term. Consequently, salt cedar management in face of potentially increased salt loading should be a research and management priority.

In conclusion, management of coalbed methane wastewater needs to incorporate an understanding of the unique ecology of the Powder River. Furthermore, the river's importance to several rare and declining species should also inform its management. Results of evaluations of the biological, physical, and chemical integrity (Confluence, 2004) provide an initial screen that identifies potential negative effects and additional research needs. Failure to employ an adaptive management approach based on continued assessment and monitoring poses undue risk to water quality and aquatic life and is not consistent with the explicit objective of the Clean Water Act.

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Coalbed methane produced waters: Management options for sustainable development

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Water produced during coalbed methane development is a valuable resource that can provide benefits but can also have harmful impacts. This report presents a synopsis of the relationship between coalbed methane development and produced water quantity and quality. Based on an extensive search of literature and other information, disposal and use options for produced water are presented, as are potential environmental, social, and legal impacts from those options. Alternatives for treatment of produced water to satisfy discharge and/or use requirements were researched and existing or developing water treatment and technically and economically feasible disposal technologies were identified. The implications for discharge and use from a regulatory standpoint are also considered. The combined information is analyzed on the basis of "sustainable development" and presented in terms of disposal and use options that lead to more or less sustainable outcomes. The results show that those practices that lead to less aquifer depletion and greater recharge, or employ water treatment if necessary to meet standards for disposal or use, lend themselves more to the principles of sustainable development. The report concludes that technological implementation and progress, regulatory reform, and industry and citizen dialogue are needed to encourage sustainable CBM development.

Dispelling CBNG production water myths using SO_2/sulfurous acid generators/sulfur burners

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Introduction

Recently, Harmon SO_2/Sulfurous Acid Generators, more commonly known as sulfur burners, have been successfully used to amend Powder River Basin coalbed natural gas (CBNG) production water for direct soil application. While this technology has been used in agriculture for nearly fifty years, a great degree of confusion remains as to what they can do and the advantages they may have over other methods. This confusion appears to stem from using previous information that is flawed and based on certain myths. By exposing these myths, it will become apparent as to what this equipment actually does, and why it truly is a viable option for the management of water and soil.

The Three Myths

Myth # 1: Reducing the amount of Total Dissolved Solids in CBNG production water is more important than reducing its Total Alkalinity.

The major constituents of water consist of various electrically charged materials, called cations and anions, and their sum total is measured as Total Dissolved Solids or TDS (**Figure 1**). Some of these materials, calcium (Ca) and bicarbonates (HCO_3), because of their opposite charges, have an attraction to bond with each other forming lime (**Figure 2**). It is important to focus on TDS's Total Alkalinity component (bicarbonates and carbonates) as each 1 meq/L of bicarbonates (61.02 ppm) approximates 200 pounds of lime-forming potential for every acre foot of water[1], or 7758 forty-two gallon barrels applied (**Figure 3**). For example purposes, CBNG production water found in the Powder River Basin has been analyzed to contain 20 meq/L of bicarbonates. Left untreated, this type of water would contribute nearly 4000 pounds of lime to the soil.

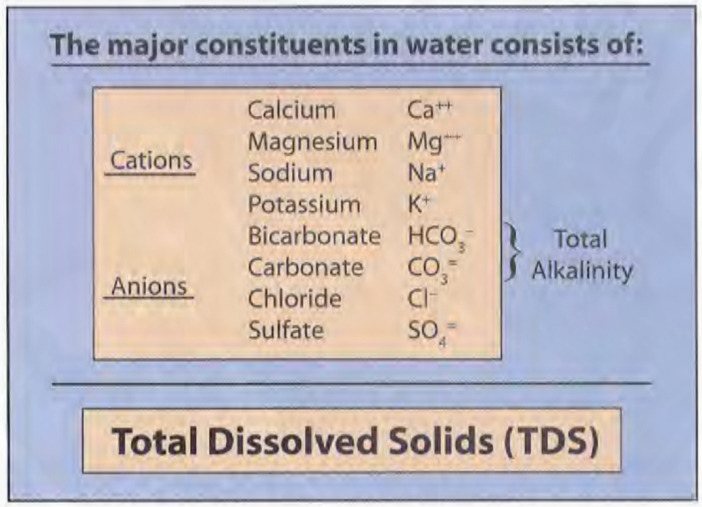


Figure 1. The major constituents in water.

Since the only place for lime to form would be in the soil's existing pore spaces, as they begin to seal and plug, a degrading domino effect occurs–it lowers the overall amount of active available calcium from dominating soil exchange sites and increases the Sodium Adsorption Ratio (SAR); it slows water infiltration rates, causing shallow and uneven penetration, water-logging, and increases surface evaporation which then causes more salts to accumulate at the soil/air interface; it decreases the soil's water holding capacity, which increases the possibility for water to runoff; and it suffocates vital aerobic microbial activity needed for healthy soil.

To prevent the above from occurring simply requires a way to keep lime from forming, and the easiest and most cost effective way would be to focus primarily on eliminating the bicarbonate and carbonate levels

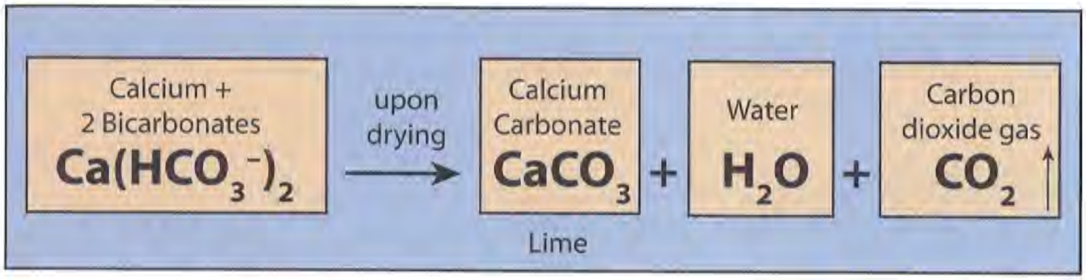


Figure 2. The formation of $CaCO_3$.

from the production water with an acidifying agent, and to amend it to a pH that is similar to rain. By examining rainwater's influence on soil, it will provide us with the most reliable scientific model as to what will happen, but also, show us the reason why greater emphasis should be placed on reducing and/or eliminating CBNG production water's Total Alkalinity instead of focusing primarily on TDS.

Contrary to what many people believe, normal rainwater is naturally acidic and has a normal pH that averages about 5.6 (**Figure 4**). Rain is referred to as the universal solvent because the free hydrogen in rainwater essentially has been dissolving lime from soil for billions of years. By dissolving lime throughout the soil profile, greater porosity is created, water and nutrients penetrate deeper, salts can leach, and oxygen and carbon dioxide can exchange. If rainwater were neutral or alkaline this could not occur. Since soils will always acquire the characteristics of the materials applied upon it, rainwater, including the lack of it, has and continues to remain the most influential factor of all. This is why arid and/or semi arid regions tend to have soils that are alkaline or basic, and have soil pHs greater than 7.0, and why high rainfall areas have soils that are acidic, with pHs lower than 7.0 (**Figure 5**).

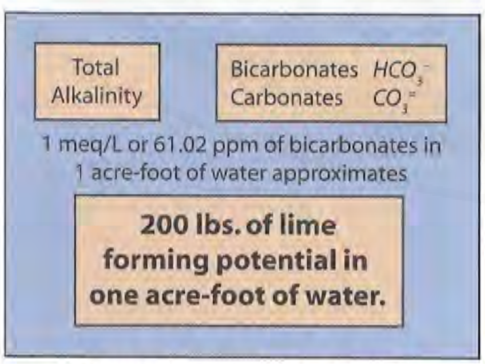
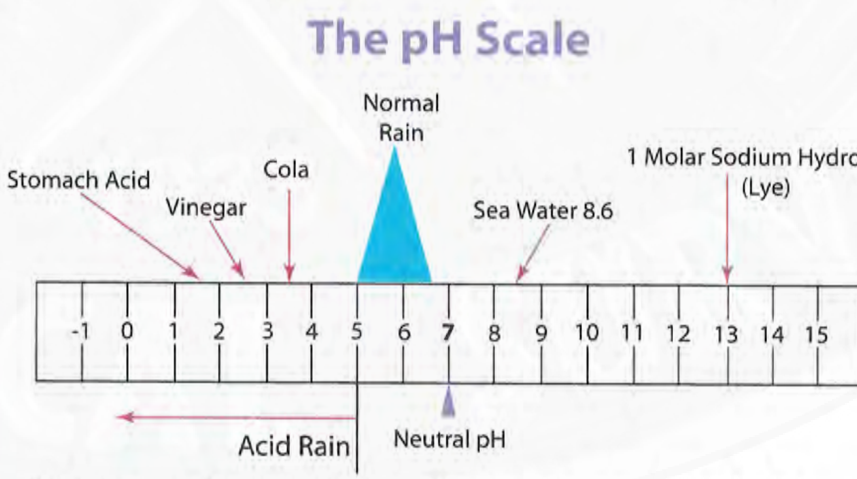


Figure 3. 1 meq./L (61 ppm) bicarbonates approximates 200 pounds of lime.

There are instances where the acidity of rainwater can become harmful, such as when rain falls in regions where extensive fossil fuel burning (coal) occurs (**Figure 6**). Atmospheric sulfur dioxide (SO_2) acidifies rainwater even further (< 5.0) and it falls uncontrolled onto lakes, rivers, creeks, forests, etc. With soils already in a naturally acidic state, this type of rain accelerates the leaching of soil minerals, which leads to nutrient imbalances and conditions in which metals such as aluminum become more soluble and toxic to fish, wildlife, and vegetation. However, with modern irrigation equipment, combined with the proper use of calcium providing soil amendments, we can control precisely the volume, rate, and where to apply CBNG production water after it has been acidified.

While acidification cannot reduce the production water's existing salinity, doing so will allow the salts to become manageable. This can be done by providing a supplemental calcium source such as gypsum ($CaSO_4$)



pH is a measure of how much hydrogen ion is in solution and is equal to the negative log of the hydrogen ion concentration. The term pH is derived from the French words "pouvoir hydrogene" meaning "power of hydrogen." A pH scale extending from 0 to 14 covers the range of pH of most common solutions. A few extremely acidic solutions such as concentrated battery acid can actually have a negative pH, and a few highly caustic (basic) solutions have pH values of 15 or even slightly higher.

This scale was modified from Pennsylvania State University, http://www.ems.psu.edu/info/explore/acidr/phscale.gif.

Figure 4. Pennsylvania State University pH scale.

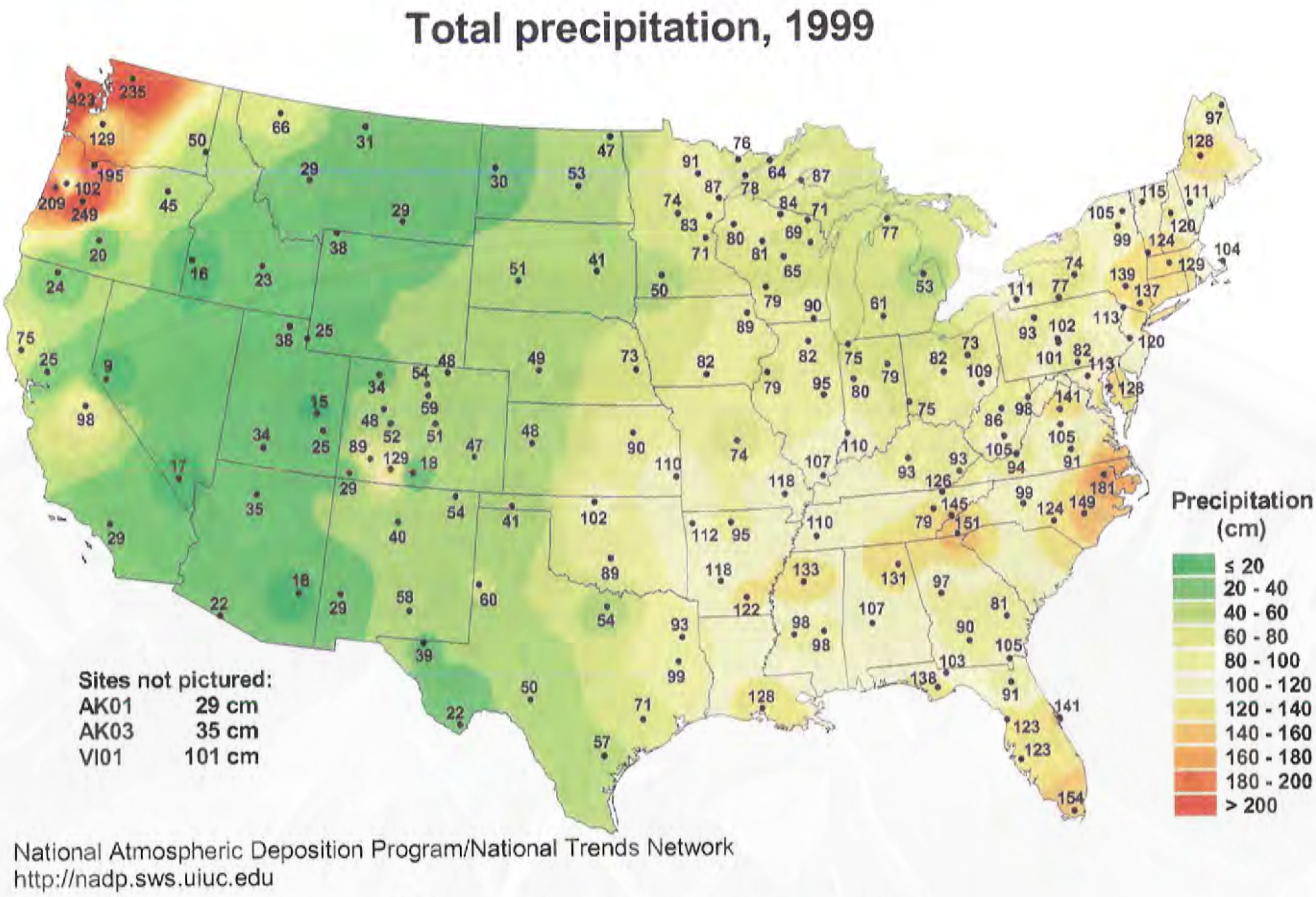


Figure 5. Total precipitation for 1999, NADP.

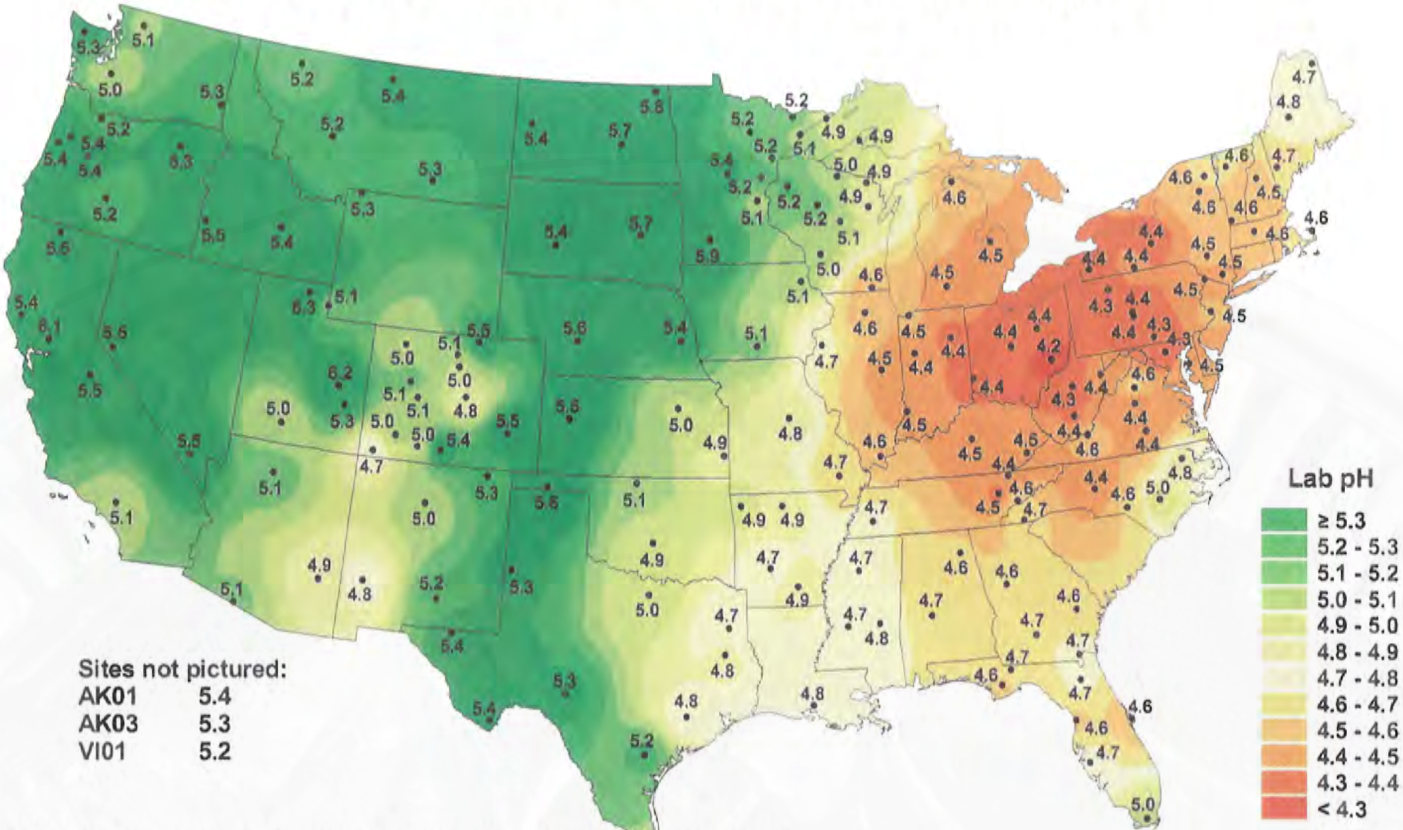
to counter the high sodium (Na) content contained in most CBNG production waters.

Thus, as it relates to direct soil applications, reducing the TDS of CBNG production water instead of its Total Alkalinity component may be based more on myth than fact.

There are several ways to introduce acidification: by using soil amendments; amending the water; or doing both.

The most common way has been to apply sulfur directly on soil that will be irrigated. While it is simple and can work, there are some important points to consider. First, the acidifying reaction using soil sulfur requires the aid of Thiobacillus bacteria to oxidize the sulfur, a process that is slow and oftentimes requiring many years for a complete reaction to occur. Second, in an effort to accelerate this reaction, some soil sulfurs may be manufactured using Bentonite clay (10%) to bond fragmented sulfur pieces (90%) together, and upon water contact disintegrates and releases the sulfur particles. This type of sulfur is designed to allow for a greater surface area for Thiobacillus decomposition. The residual effects of this additional material to the soil should be accounted for. Third, since this method requires that a consistent level of bacterial activity is needed to create and maintain the acidifying reaction, varying soil temperatures will have an effect.[2] As a result, this method may not be capable of neutralizing the volume and rate in which bicarbonates/carbonates are introduced. Fourth, this method is unevenly distributed which can lead to an over application of material in certain locations. Fifth, as the sulfur particles migrate downward, some of the acidifying reaction takes place below the surface, instead of at the soil/air interface where it is needed the most. Sixth, because the acidifying reaction with this method can only take place at the soil, it allows bicarbonates/carbonates to physically make contact with the soil and any supplemental calcium amendments that may have been added. This allows the formation of lime to occur. Seventh, soil pH affects many microorganisms and because of the tremendous volume of sulfur needed during application, the acidifying reaction can be toxic and disruptive in

Hydrogen ion concentration as pH from measurements made at the Central Analytical Laboratory, 1999



National Atmospheric Deposition Program/National Trends Network
http://nadp.sws.uiuc.edu

Figure 6. Hydrogen ion concentration, 1999, NADP.

maintaining a healthy and diverse microbial population.[3]

The Harmon SO_2/Sulfurous Acid Generator is a unique method designed to produce sulfurous acid or (H_2SO_3) a mild acid that is easy to handle. It is important to note that this equipment does **not** produce sulfuric acid (H_2SO_4), a strong acid that is extremely corrosive and very difficult to handle. Sulfuric acid is produced using a separate and different process. Although these two acids appear similar, the comparative difference between them is that when sulfuric acid is introduced to water, the two hydrogen ions ($2H^+$) are immediately released to react with bicarbonates and carbonates (HCO_3 and CO_3) that are present, which then produces water (H_2O) and carbon dioxide (CO_2). As this reaction occurs, carbon dioxide gasses from the water, the Total Alkalinity and pH is reduced, and the remaining sulfate (SO_4) is left in an aqueous solution that is normally adjusted to a pH range of 6.5.

Conversely, sulfurous acid (H_2SO_3), because of the imbalance charge it has a slightly different sequence. It releases a single hydrogen (H^+) to react and lower the pH of the water, the other hydrogen (H^+) remains bonded in the form of Bisulfite (HSO_3) in solution. Although this solution may be adjusted to a pH of 6.5, the overall acidity of the solution is actually greater, because when this water is finally applied to the soil, Thiobacillus bacteria completes the reaction by oxidizing (O_2) and converting the Bisulfite into sulfate (SO_4) and upon doing so, releases the additional acidity (H^+) into the soil/water solution.[4] The delayed release of this additional acid is significant because with this method, while it creates a mild acid that is safe to use with irrigation system components, it is also able to deliver water that is lower and similar to the acidity of normal rain.

A comparison of materials indicates that it requires 3.06 tons of sulfuric acid to duplicate the same acidifying power of 1 ton of sulfur.[5] The Harmon SO_2/Sulfurous Acid Generator completely oxidizes elemental sulfur and combines it with the water which causes an immediate acidifying reaction to occur; reduces and/or eliminates the bicarbonates and carbonates from CBNG production water so they can never be applied to the soil; is capable of delivering the additional acidity necessary to neutralize and dissolve soil lime formations as well; provides a more even and uniform distribution of acid; and is safe and cost effective. This is why this technique has significant advantages over all acidification methods (**Figure 7**).

However, since every situation is different, no single method can solve every problem and each method should be viewed as a "tool" within the CBNG producer's overall toolbox. Regardless of the method selected, all will require continuous soil monitoring to insure that sufficient acidification is maintained, and the scientific model and environmental goals for that location are not in conflict.

Myth #2: Applying CBNG water on soil will only degrade it and will never improve it.

While it is true that direct applications of untreated CBNG production water on soil would severely degrade it, the opposite would occur if adequate steps were taken to acidify and reduce its Total Alkalinity component prior to its application. Negating the high sodium content of this water by adding a sufficient supply of supplemental calcium such as gypsum to the soil can help improve the soil as well.

By addressing both of these issues, soils receiving this improved water would essentially be receiving an extra amount of rainfall over and above its annual total (**Figure 8**). Eventually, this extra water should help lower the existing soil pH from being alkaline to a range that is better suited for agricultural crop production, as well as increasing its infiltration rate and water holding capacity. Optimal agronomic conditions that are considered ideal for most crops such as alfalfa (the most logical choice for this region) is when the soil pH is about 6.5.[3]

When more pore space is created, oxygen and carbon dioxide can exchange, and nutrients become more available. This enables a greater diversity of microorganisms to flourish and multiply. As the microbial population increases, they provide a food source for other microorganisms, and as a result, their combined activity not only helps to hold the soil together, but also develops healthier and more fertile conditions as well. Again, rain's natural acidity created these environments. This is why if we apply acidified CBNG water to the soil, and provide enough supplemental calcium to counter the high levels of sodium, water will infiltrate deeper, the salts should leach away, and it is reasonable to expect soil conditions to improve over time and not degrade. When the CBNG play is over, and the only water that reaches the soil is rain, the soil, because of its lower pH, increased porosity, larger water holding capacity, and microbial diversity, is likely to be more productive and develop more yearly vegetation compared to soils that did not (**Figure 9**).

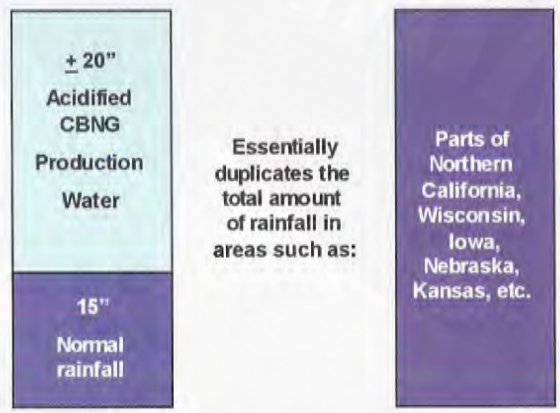


Figure 8. Total application of water.

Figure 7. Harmon Model 30 amending CBNG production water in Pit Reservoir.

Myth #3: CBNG production water is just a waste product with virtually no value or use and disposing of it is all that we can do.

Perhaps the reason why this industry is having so much difficulty moving forward is because there is a general view among local citizens that CBNG produc-

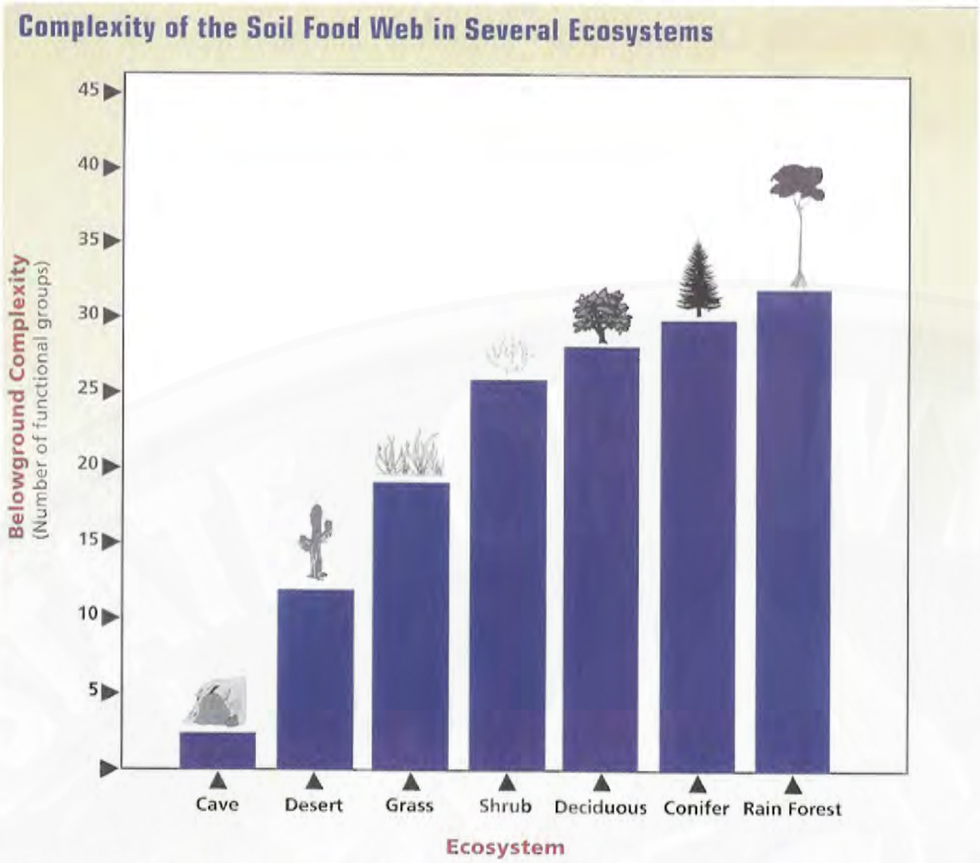


Figure 9. Complexity of the soil food web in several ecosystems, from Dr. E. Ingham.

tion only benefits the producers, and they have very little to gain.

This is precisely why the industry, as a whole, needs to develop ways to allow as many people as possible to benefit from every aspect of it, and there is absolutely no finer way to reconnect people, and to help them to resolve their differences, than to enable them to receive a benefit from all of the water produced.

These benefits can be quite significant, especially in arid and semi-arid regions prone to drought. They include: a new water source for agricultural crop production; increasing alfalfa hay production; decreasing the pressure to over graze; the potential to utilize these waters for increasing wildlife habitat; lessen demand on existing surface water supplies; economic benefit to local businesses and communities; and help our nation to achieve its energy goals while becoming less dependent on foreign sources and remaining environmentally sound (**Figure 10**).

In closing, by recognizing the influential role of the Total Alkalinity as the main culprit instead of the overall TDS, and taking the necessary steps to eliminate it so it can never be applied, it is possible to manage and transform CBNG production water from being a waste into something useful, highly beneficial, and of great value.

References cited

[1] A & L Western Agricultural Laboratories

[2] Soil and Water Conservation Society, Soil Biology Primer, p.9

[3] USDA NRCS, Soil Quality Indicators: pH, January 1998

Figure 10. Irrigating alfalfa using sulfurous acid treated CBNG production water.

Trip, tricks, and traps of using sulfur burners for treating CBNG discharge water prior to irrigation application

Neal E. Fehringer–Fehringer Agricultural Consulting, Billings, Montana

Bicarbonates in the CBNG produced water will combine with soluble calcium that has been applied to lower SARs in the produced water. Lime, which is water insoluble, is produced when bicarbonates complex with calcium. Thus, the calcium is no longer in the soil solution to offset the light SARs. Two methods are being used to reduce or eliminate bicarbonate levels. These are using sulfur burners to treat the water prior to application and applying 90% sulfur to the soil surface to reduce bicarbonates after application. Sulfur burners create sulfur dioxide that is converted to sulfurous acid as the raw discharge water passes through the burner. The treated water is returned to the reservoir to mix with predominately untreated water. Burners are used until the sufficient water has been treated to reduce the bicarbonate levels. This study quantifies the chemical changes in the pH, bicarbonate, EC, and SAR levels of the produced water prior to mixing with calcium amendments and after amendment application. Aeration (or active mixing) substantially reduces the bicarbonates and pH in a few days. Passive mixing results in erratic pH and bicarbonate level reductions over a three-year period.

Countercurrent ion exchange applied to SAR modification in CBM produced water in the Powder River Basin, Wyoming

Douglas Beagle, Operations Manager–EMIT Water Discharge Technology, LLC., Sheridan, Wyoming

Development of coal bed natural gas (CBNG) reserves in the Powder River Basin (PRB) of Wyoming produces associated waters with varying levels of sodium and other cation constituents that may be desirable to remove so that the water can be provided for beneficial use. The Higgins Loop ™ Continuous Ion Exchange Technology offers a proven, economical, and efficient process for purification of produced waters without the generation of large waste streams. The treated water becomes a valuable asset.

History

In 1951, Irwin R. Higgins, a chemical separation specialist for the Atomic Energy Commission, developed an equipment system that allows ion exchange resins to be used in a continuous, countercurrent process. He received the first of 50 patents for the invention that year. The Higgins Loop™ System, as it is called now, was the first technology developed by the U.S. Government that was sold and commercialized by a private business. Over the past 5 decades, the Higgins Loop™ has been used for purifying plutonium, extracting uranium, producing chemicals, purifying drinking water, and many other applications. Severn Trent Services acquired the technology in 1991. EMIT Water Discharge Technology, LLC licenses the technology from Severn Trent Services for CBM water treatment.

EMIT process

The process used by EMIT to modify SAR levels consists of four process steps (**Figure 1**): Water degassing and separating; cation exchanging; pH controlling; and water blending. Water is degassed and separated in the first step to remove methane gas and provide a water stream for blending to the design SAR. Cations are removed in the second step, which is described in greater

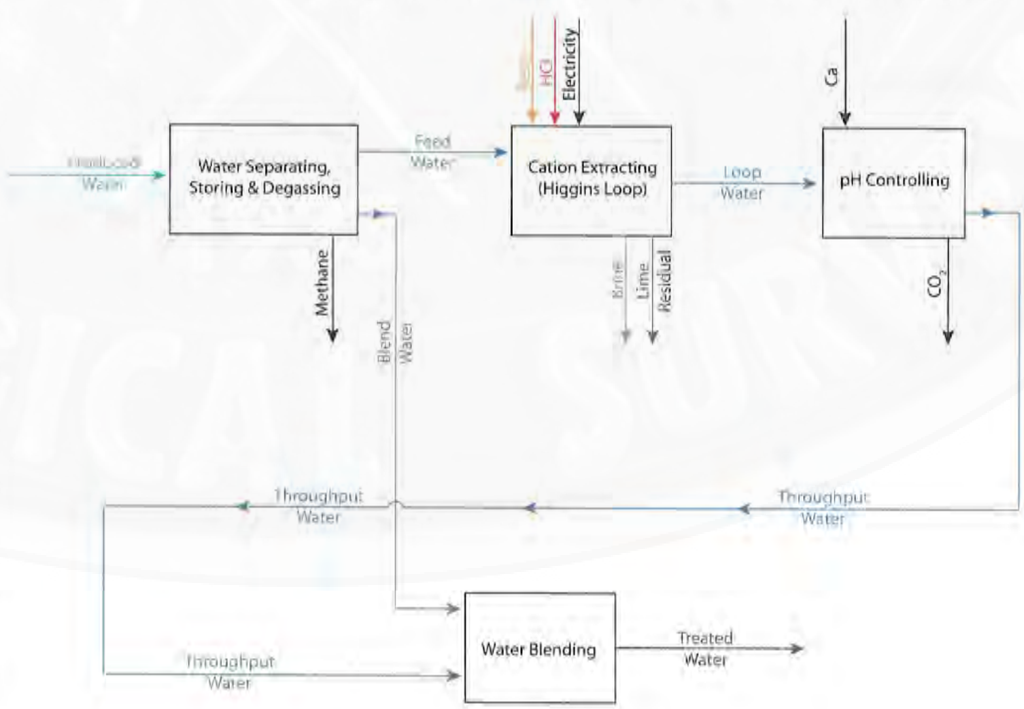


Figure 1. EMIT Process Steps

detail below. In the third step, pH levels are raised and Ca (calcium) is introduced; the water is blended to the appropriate SAR in the final step in preparation for discharge or land application.

Higgins Loop™ process

Produced water containing high Na (sodium) levels is fed into the adsorption zone within the Higgins Loop™ (**Figure 2**) where it contacts strong acid cation resin which loads Na + ions in exchange for H+ (hydrogen) ions. Treated water leaves the loop with approximately a 90% reduction in Na levels. Concurrent with adsorption, in the regeneration section of the Higgins Loop™, Na loaded resin is regenerated with hydrochloric acid to produce a concentrated waste stream which is less than 1% of the throughput water volume. Regenerated resin is rinsed with water prior to reentry into the adsorption zone to remove acid from its pores. As resin in the adsorption zone becomes loaded with Na, the flows to the Higgins Loop™ are interrupted to allow advancement or pulsing of the resin bed through the loop in the opposite direction of liquid flow. Liquid flows are restarted after resin pulsing is complete. Loaded resin is backwashed to remove fines and debris that may have been present in the feed water prior to regeneration. The process is controlled by PLC (programmable logic controller) using process variables of pH, flow, conductivity, and time. Treated water is slightly acid due to its increased H+ ionic strength. The pH is raised and Ca added by passing the treated water through a limestone bed in the pH controlling process step. Brine regenerate is neutralized and disposed of in a Class I injection well. **Figure 3** shows a water analysis before and after treatment with the Higgins Loop ™ and the pH controlling process steps.

Operating results

Operating results have been compiled for the two units that have been in service since January of this year. In order to best serve the CBNG operator, a strong emphasis on process efficiency and effectiveness is required. Process efficiencies achieved through continuous improvement of the operating process reduce the cost to operate and improve runtimes. High percentage runtimes allow the operator to produce gas without interruption. Runtimes for the two units have averaged 98.3% and 99.0% for Loop 1 and 2 respectively (**Figure 4**). While throughput volumes have increased, process improvements have reduced brine generation and acid consumption (**Figure 5**).

Regenerate brine as a percentage of throughput volume has decreased as process improvements have increased the NaCl content of the brine (**Figure 6**). Na extraction has remained sufficiently high to meet SAR target requirement as HCl usage has decreased (**Figure 7**). Acid consumption per billion barrels (bbl) of

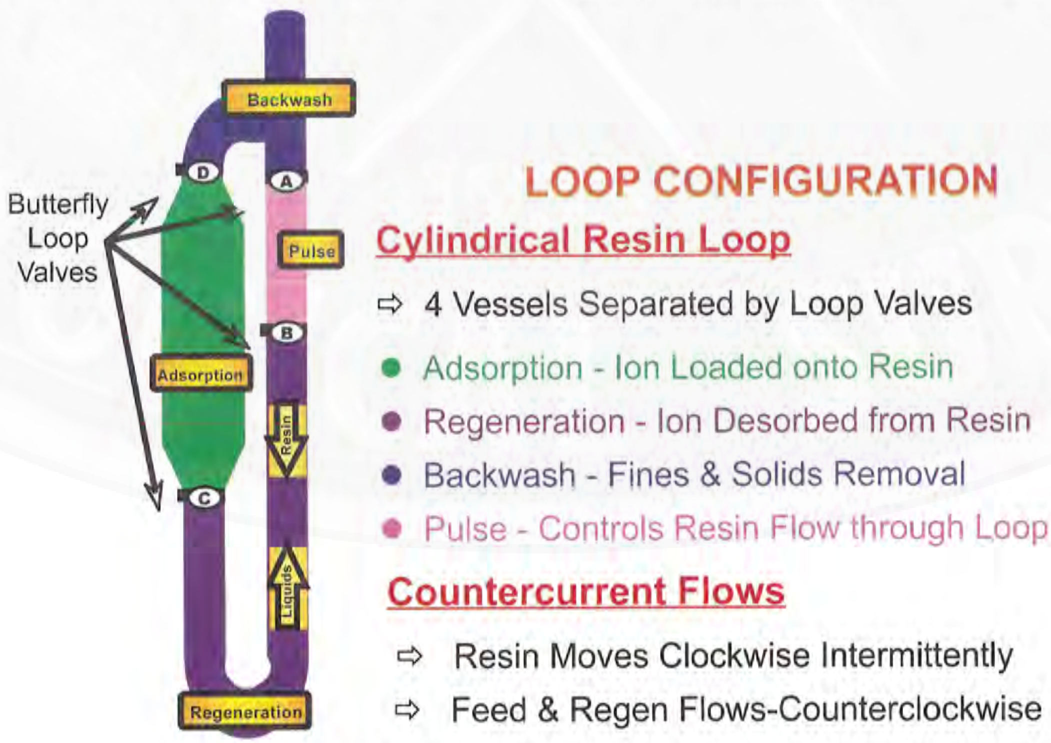


Figure 2. Higgins Loop ™ ion exchange systems.

EMIT Water Discharge Technology

TABLE 1

Higgins Loop ™ Process Performance

Sample Source: **Campbell County CBM Produced Water** Date: **June 2004**

			Raw Feed Water	Throughput Water
Cations	**Sodium**	mg/l	**446**	**42**
	Calcium	mg/l	**25**	**88**
	Magnesium	mg/l	**14**	**ND**
Anions	**Bicarbonate**	mg/l	**1300**	**310**
	Chloride	mg/l	**19**	**28**
	SAR		**17.9**	**1.2**
	pH		**7.93**	**6.32**
Electrical Conductivity		μmhos/cm	**1900**	**576**

Figure 3. Higgins Loop ™ process performance. Lab analysis results via Energy Laboratories and Inter-Mountain Laboratories.

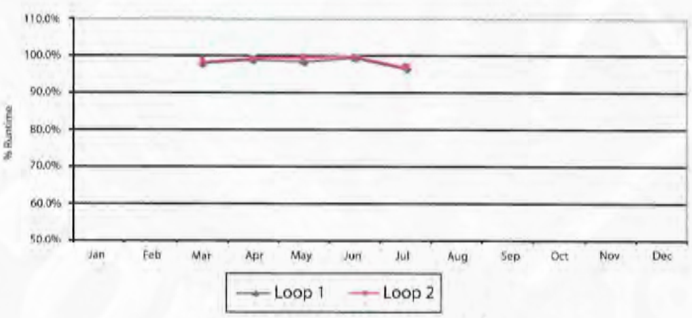


Figure 4. Runtime graph.

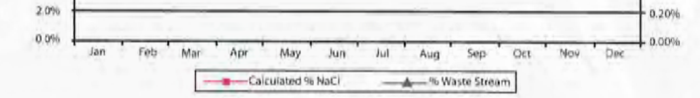


Figure 6. Brine graph.

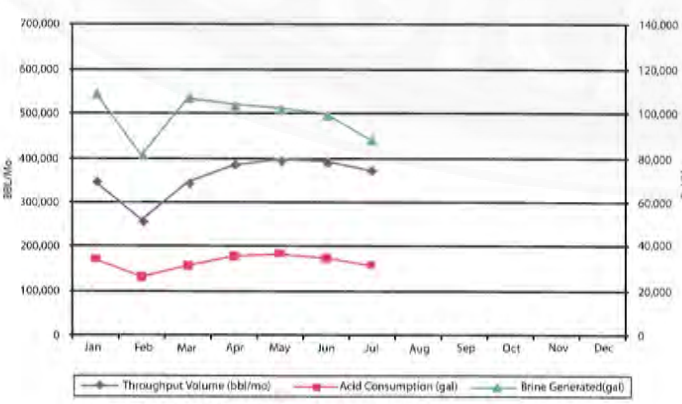


Figure 5. Monthly process volumes graph.

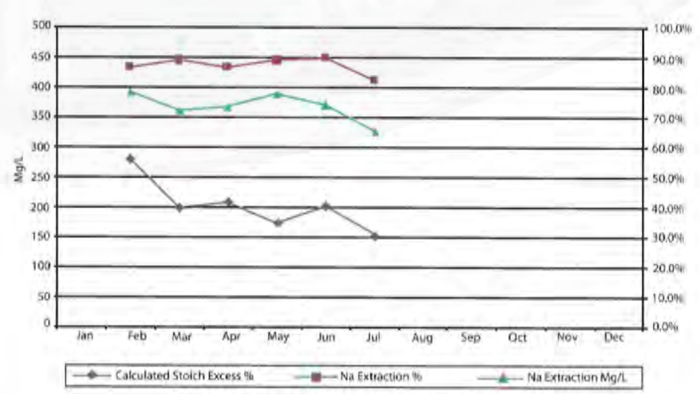


Figure 7. Na extraction graph.

throughput water volume has decreased indicating increased process efficiency (**Figure 8**).

Unit throughput

There are two sizes of Higgins Loop™ units deployed, 3012 and 6024. The first number in the series (30 or 60) represents the diameter in inches of the adsorption vessel and the second number (12 or 24) is the diameter in inches of the rest of the process vessels. **Figure 9** shows the relationship between cation load of CBNG water and throughput capacity of the two unit sizes. Other determining factors for total treated water volume would be discharge or land application SAR requirement and Ca uptake in the pH controlling process step.

Summary

The EMIT Water Discharge Process featuring the Higgins Loop™ process is an effective way to treat CBNG water because it is flexible enough to meet differing SAR requirements; it generates minimal waste; has consistent, predictable results and has high runtimes that result in higher gas production rates. The treated water price per bbl includes all equipment and services including brine concentrate disposal and is based upon produced water quality and quantity and treating requirements.

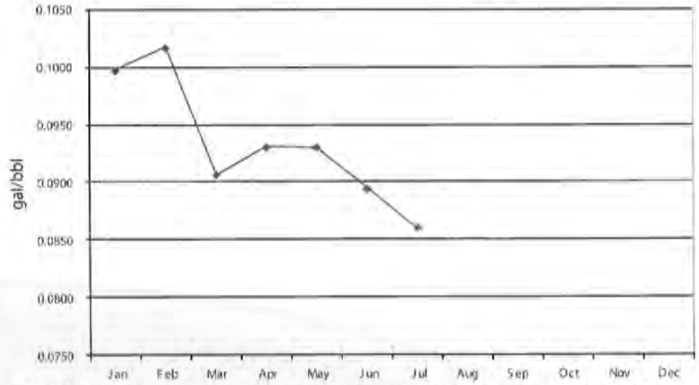


Figure 8. Acid consumption (gallons) per throughtput bbl.

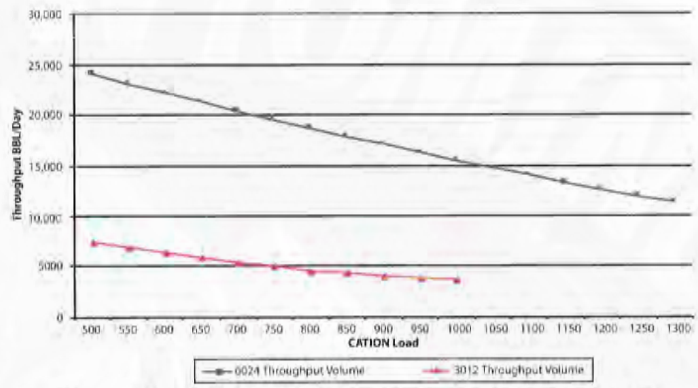


Figure 9. Unit throughput volume v. cation load.

Re-injection of CBNG-produced water: Thinking small

Joel E. Adams, Hydrogeologist, and Thomas J. Osborne, Principal/Hydrogeologist–
HydroSolutions, Inc., Red Lodge, Montana

Injection of produced water plays a minor, but growing role in coalbed natural gas (CBNG) production in the Powder River Basin. Development is occurring in portions of the basin in which surface discharge is not an option. Where consumptive use via irrigation is not viable, CBNG producers are limited to water management solutions such as off-channel impoundments, water treatment, and injection.

Injection wells are regulated under the EPA Underground Injection Control, or UIC program. In Wyoming, the UIC program is administered by the Wyoming Department of Environmental Quality (WDEQ). Injection wells for CBNG produced water will fall under either a Class II or Class V UIC permit. The State of Wyoming has Class V General Permit for injection of CBNG produced water into the Wasatch, Fort Union, and Fox Hills formations. In Montana, the UIC program is administered by the EPA. There are no general UIC permits in place in Montana.

A query of the WDEQ UIC database shows that as of December 2003, approximately 320 injection wells had been permitted for injecting CBNG produced water. Approximately 170 of those permitted wells had been constructed and were considered active injection wells.

Wolverine Operations, LLC currently operates four injection wells in two fields; the Spotted Horse field in Campbell County, and the Brookstreet field in Sheridan County. Injection rates in the Spotted Horse field range from approximately 1700 to 4000 barrels per day (bpd) (50 to 117 gpm) with well-head injection pressures of 0 to 170 psi. Injection rates in the Brookstreet well range from approximately 400 to 2000 bpd with injection pressures of 220 psi.

Many of the CBNG injection wells constructed to date are over-dimensioned. Using a maximum flow velocity criteria of 5 feet per second to minimize friction loss, a 3-inch diameter well would suffice in all of the cases presented above. Significantly reducing the cost of injection well construction would likely result in greater utilization of injection as a water management option. The wells with higher injection pressures would require the use of steel casing, whereas wells with injection pressures of 100 psi or less could be completed with PVC casing. However, safety considerations would likely make use of PVC less desirable.

Research and development aimed at solving some of the barriers to large-scale application of injection will be necessary. Specific areas of research that would be beneficial include the following:

- Minimizing the occurrence of iron-fixing bacteria;
- Centralized water treatment and distribution systems;
- Optimizing injection well construction; and
- Improving methods for identifying potential receiver zones.

CONCURRENT SESSION—Session 3: Water use, soils, and wildlife

Wyoming Union, Yellowstone Ballroom

Co-Chairs: Richard Zander, U.S. Bureau of Land Management and Larry Munn, University of Wyoming

Editor's note:	*Titles of presentations shown on this page may be somewhat different from the written articles published in this volume.*
1:30 p.m.	Quality of CBM product water for land application–*K.J. Reddy, University of Wyoming*
1:50 p.m.	Interaction of coalbed methane waters with soils in the Powder River Basin–*J.D. Stednick, Colorado State University; W.E. Sanford, Colorado State University; A.J. Neuhart, Colorado State University*
2:10 p.m.	*Controlling sodicity during irrigation with CBNG produced water–*Dina Brown, KC Harvey, Inc.; Kevin Harvey; KC Harvey, Inc*
2:30 p.m.	Soil chemistry changes after CBNG water application ceases–*Neal E. Fehringer, Fehringer Agricultural Consulting*
2:50 p.m.	BREAK
3:20 p.m.	Preserving irrigation water quality down stream of coalbed natural gas operations: Tongue River in Montana–*William M. Schafer, Schafer Limited; Neal Fehringer, Fehringer Agricultural Consulting; Kevin C. Harvey, KC Harvey Inc.*
3:40 p.m.	*West Nile Virus: An emerging issue in sage grouse conservation–*David Naugle, University of Montana; Cameron L. Aldridge, University of Alberta; Brett L. Walker, University of Montana; Todd E. Cornish, Wyoming State Veterinary Laboratory; Brendan J. Moynahan, University of Montana; Matt J. Holloran, University of Wyoming; Kimberly Brown, Thunderbird Wildlife Consulting; Gregory D. Johnson, Montana State University; Edward T. Schmidtmann, U.S. Department of Agriculture; Richard T. Mayer, U.S. Department of Agriculture; Cecilia Y. Kato, U.S. Department of Agriculture; Marc R. Matchett, U.S. Fish and Wildlife Service; Thomas J. Christiansen, Wyoming Game and Fish Department; Walter E. Cook, Wyoming Game and Fish Department; Terry Creekmore, Department of Heath; Roxanne D. Falise, Bureau of Land Management; E. Thomas Rinkes, Bureau of Land Management; Mark S. Boyce, University of Alberta*
4:00 p.m.	*West Nile Virus in the Powder River Basin–*Todd Cornish, Wyoming State Veterinary Laboratory and University of Wyoming*
4:20 p.m.	Coalbed methane impoundments, mosquitoes, and West Nile Virus: An Emerging Problem?–*Edward T. Schmidtmann, U.S. Department of Agriculture; Gregory D. Johnson, Montana State University; C.Y. Kato, US Department of Agriculture; Brett Walker, University of Montana; David Naugle, University of Montana; John E. Lloyd, University of Wyoming*
4:40 p.m.	Powder River Basin wildlife protection, monitoring, & research–Thomas Bills, U.S. Bureau of Land Management and CBNG Interagency Wildlife Taskforce

* Written paper was not available for this volume

Quality of CBM product water for land application

K.J. Reddy–University of Wyoming, Laramie, Wyoming

Several alternatives are proposed for the management of coalbed methane (CBM) produced water within the Powder River Basin (PRB), Wyoming. These options include surface land application (e.g., irrigation), aquaculture, and livestock and wildlife watering. The objective of this study was to examine the quality of CBM discharge water across the PRB to evaluate its suitability for land application. CBM discharge water samples from different watersheds within the PRB were collected and monitored for salinity and sodicity over a period of several years. Data gathered from this research will be used to determine how quality of CBM discharge water changes as a function of watershed properties. In addition, relationship between EC, sodium, calcium, magnesium, and sodium adsorption ratio (SAR) in CBM discharge water will be discussed.

Interaction of coalbed methane waters with soils in the Powder River Basin

J.D. Stednick, W.E. Sanford, and A.J. Neuhart–Colorado State University, Fort Collins, Colorado

In the Powder River Basin (PRB) the produced water from coalbed methane (CBM) extraction is often discharged into stream channels and as it infiltrates or moves downstream, it interacts with in-channel and near-channel soils. As the CBM water infiltrates, it dissolves the naturally occurring salts that have accumulated over time, altering the water chemistry. Our study objectives were to chemically characterize CBM production waters, the receiving surface waters, and shallow groundwater.

Three study sites were chosen in the PRB: Little Bullwhacker Creek, Beaver Creek, and Little Thunder Creek. The CBM production waters were all classified as a Na-HCO_3 type water. The streamwater chemistry was generally similar to the discharge waters, except for a noted increase in pH. Water chemistry differences were observed between the streamwater and the shallow groundwater near the stream channels. As the CBM water interacted with the soils, there was an increase in both specific conductance and salt concentrations. The shallow groundwater was classified as a Na-SO_4 type water.

From the sites we have studied, the biggest influence on water chemistry is due to interaction of the produced waters with the soils and sediments around the channels. The significant change in water chemistry happens over a very short time and distance. As the discharge of produced water decreases, the bank storage water will exfiltrate back to the channel, continuing to add salts to the surface water, even when CBM production water is absent. CBM discharge water interaction with surface soils results in a variety of different physical and chemical processes including dissolution, exchange, and precipitation that may affect downstream water quality and uses.

Soil chemistry changes after CBNG water application ceases

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Many scientists, environmentalists, farmers, and ranchers are predicting what negative impacts will occur if CBNG water is applied to the soil. Sodium adsorption ratio (SAR) and EC increase with the application of the produced water. SAR can be lowered by the application of gypsum, as long as the bicarbonates have been substantially reduced. The application of gypsum will increase the soil EC. This presentation quantifies soil chemistry changes that occurred when produced water application ceases. Nine fields with SARs greater than 10 in the fall of 2002 were sampled again in April 2003. The average SAR reduction in those six months was 39%. EC declined approximately 30%. Twenty-seven fields that did not receive water in 2003 but had SARs ranging from 8-15 in the fall 2002 were sampled again in fall 2003. The average SAR reduction was 47% in 12 months. SAR reductions were greater where gypsum (54%) had been applied, than in fields where gypsum had never been applied (39%). EC declined in fields that did not have gypsum applied. EC remained neutral in fields that had had gypsum applied. These 27 fields will be sampled again in fall 2004.

Preserving irrigation water quality down stream of coalbed natural gas operations: Tongue River in Montana

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Abstract

Coalbed natural gas (CBNG) production began in the upper Tongue River Basin in the late 1990s in Wyoming and Montana. Irrigators in Montana have expressed concerns about the potential effects of CBNG development on the quality of irrigation water. In response, Fidelity Exploration & Production Company commissioned the development of a comprehensive Tongue River Agronomic Monitoring and Protection Program (AMPP). The AMPP involves volunteer irrigators located from the headwaters to the mouth of the Tongue River.

The AMPP, designed to be a long-term initiative, consists of three components. The first component, called Tier 1, includes soil sampling, crop inspection, yield measurements, and fertilizer/agronomic recommendations. Tier 2 consists of detailed spatial and vertical soil sampling to detect changes in soil chemistry that may occur as a consequence of CBNG activity. Tier 3 of the AMPP is a series of test plots that evaluate the effects of various combinations of groundwater produced by CBNG operations and Tongue River water. First year fall and spring soil sampling results, ambient Tongue River water quality, and Montana's irrigation quality standards will be discussed.

Introduction

The Powder River Basin in Wyoming and extreme southeastern Montana hosts extensive reserves of natural gas in coal seams that are commonly found in the Fort Union Formation. The coal seams must be de-pressurized by pumping groundwater to facilitate release of the CBNG or methane contained in the coal. This *produced water*, groundwater pumped from the coal, naturally contains moderate levels of dissolved ions in which sodium is the dominant cation and bicarbonate the primary anion. The electrical conductivity (EC) and sodium adsorption ratio (SAR) of produced water in the upper Tongue River basin typically ranges from 1600 to 2000 µS/cm (µmhos/cm) and 40 to 60 respectively. The produced water is among the better quality groundwater in southeastern Montana for domestic and stock water uses.

Irrigators that rely on Tongue River water for crop and forage production have expressed concern about the potential adverse impact that CBNG development may have on irrigation water quality. In response to these concerns, the State of Montana recently promulgated numeric standards for irrigation water quality for the mainstem of the Tongue River and its tributaries (**Table 1**). The Tongue River currently meets all applicable water quality standards.

Fidelity Exploration and Production Company, a subsidiary of MDU Resources Group Inc. asked the authors to develop a testing program with the aim of helping irrigators better understand the potential effects of CBNG development on their irrigated crops. This package of soil sampling and analysis, cropping system evaluation, and interpretation is being offered at no cost to irrigators who use Tongue River water. The purpose of this program is to measure baseline soil characteristics. Subsequent soil sampling will help identify and manage any soil chemical trends related to CBNG development that could impair future crop yields.

The soil and crop monitoring and assessment program consists of three levels of detail. Tier 1 sampling and assessment consists of basic soil sampling, crop inspection, and development of crop management recommendations. Tier 2 includes a soil sampling program

Table 1. Numeric water quality standards for EC and SAR in the Tongue River.

Reach/Season	Electrical Conductivity (µS/cm)			Sodium Adsorption Ratio		
	1974-2003 Average	Monthly average criterion [3]	Instantaneous maximum criterion [3]	1974-2003 Average	Monthly average criterion [3]	Instantaneous maximum criterion [3]
March through October (irrigation season)						
Tongue River Reservoir [1]	530 [1]	1000	1500	0.7 [1]	3.0	4.5
Tongue River Mainstem [2]	685 [2]	1000	1500	1.1 [2]	3.0	4.5
November through February (non irrigation season)						
Tongue River Reservoir [1]	745 [1]	1000	1500	0.8 [1]	3.0	4.5
Tongue River Mainstem [2]	909 [2]	1500	2500	1.39 [2]	5.0	7.5

[1] *Ambient water quality at TRR measured below TR Dam, 1974 to 2003, USGS Station 06307500*

[2] *Ambient water quality for TR mainstem measured at Brandenburg Bridge, 1978 to 2003, USGS Station 06307830*

[3] *Montana Codes Annotated §17.30.670*

that is more detailed laterally, vertically, and in terms of constituents analyzed. Tier 3 studies consist of crop and forage trials that use irrigation water derived from various mixtures of Tongue River water and produced water. The purpose of the test plots is to determine a *minimum effects threshold* at which discharged CBNG water might impair crop or forage yields or quality. The purpose of this paper is to describe the first year of sampling results from the Tier 2 program.

Approach

Tier 2—Soil sampling

Sixteen Tier 2 AMPP sampling locations were selected in irrigated and dryland fields located at intervals along the Tongue River (**Figure 1**) and on major tributaries (Otter Creek, and Prairie Dog Creek). Additionally, two irrigated reference sites that use other water sources (Yellowstone and Big Horn River water) were also selected for study (**Table 2**). Participation in the Tongue River is voluntary. All cooperators are provided with Tier 1 soil sampling and crop recommendations.

Reference pedon: In each field, samples were initially collected from a reference pedon, which was sampled and described in accordance with methods and nomenclature from Schoeneberger and others (2002). Samples were obtained from each genetic horizon. Pedon samples were analyzed for selected analytes in **Table 3**. Clay mineralogy was performed on the clay-sized particles of the fine earth fraction from a surface and subsurface horizon.

Composite samples: For routine sampling of each AMPP field, a representative number of composite subsample locations were identified in a random transect within the portion of the field that consisted of a single soil mapping unit based on the County Cooperative Soil Survey. Composite sub-samples were collected at a frequency of one per 5 acres but not less than 10 samples per field (e.g. if the sampled area was less than 50 acres). Composite locations were permanently identified using a survey grade global position system. Each field sample consists of co-located composite samples from the permanent field transect. Composite samples were collected from the following depth intervals: 0 to 2, 2 to 6,

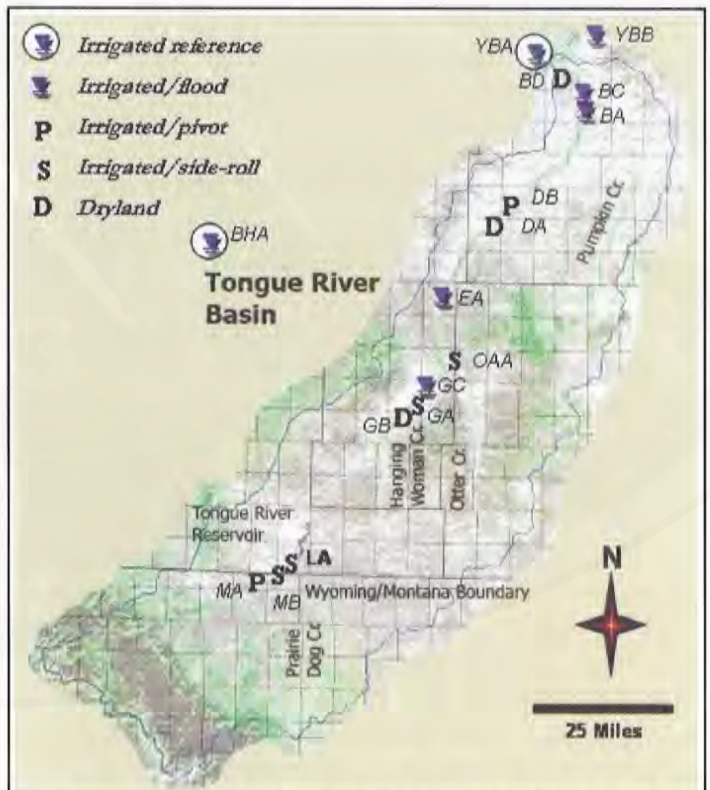

Figure 1. Landsat composite satellite image of the Tongue River basin in Montana and Wyoming. Irrigated and subirrigated lands along the river and tributaries are shown in green.

Table 2. Location of AMPP study sites.

Location	Water Source	Irrigation Method	Soil Series	Soil Classification
Tongue River Water				
BA	Tongue	Flood	Yamacall	fine-loamy, mixed, frigid Aridic Ustochrepts
BC	Tongue	Flood	Harlake	fine, montmorillonitic (calcareous) frigid Aridic Ustifluvents
BD	Tongue	Dryland	Harlake	fine, montmorillonitic (calcareous) frigid Aridic Ustifluvents
DA	Tongue	Dryland	Havre	fine-loamy, mixed (calcareous) frigid Ustic Torrifluvents
DB	Tongue	Pivot	Sonnett	fine, montmorillonitic frigid Typic Eutroboralfs
EA	Tongue	Flood	Yamacall	fine-loamy, mixed Borollic Camborthids
GA	Tongue	Side-roll	Havre	fine-loamy, mixed (calcareous) frigid Ustic Torrifluvents
GB	Tongue	Dryland	Havre	fine-loamy, mixed (calcareous) frigid Ustic Torrifluvents
GC	Tongue	Flood	Havre	fine-loamy, mixed (calcareous) frigid Ustic Torrifluvents
LA	Tongue	Side-roll	Havre	fine-loamy, mixed (calcareous) frigid Ustic Torrifluvents
MA	Tongue	Pivot	Haverson	fine-loamy, mixed (calcareous) mesic Ustic Torrifluvents
YAA	Tongue	Flood	Kobase	fine, montmorillonitic, frigid Aridic Ustochrepts
OAA	Otter	Flood	Havre	fine-loamy, mixed (calcareous) frigid Ustic Torrifluvents
MB	Prairie Dog	Side-roll	Kishona/ Cambria	fine-loamy, mixed (calcareous) Mesic Ustic Torriortherns
Reference Sites				
YBA	Yellowstone	Flood	Harlake	fine, montmorillonitic (calcareous) frigid Aridic Ustifluvents
BHAA	Big Horn	Flood	Bew	fine, montmorillonitic mesic Ustollic Haplargids

6 to 12, 12 to 24, 24 to 36, 36 to 60, and 60 to 96 inches. Samples were analyzed as described in **Table 3**. Intake rate was measured in each field at 2 to 3 locations using a tension infiltrometer.

Monitoring frequency, duration, and annual reports

All data collected in this monitoring program are available to any participating landowner or cooperating state or federal agency directly from the laboratory. A public Web site <http://www.tongueriverampp.com> also provides access to program details. Additionally, all analytical results will be published each year in a suitable report format. Field names and locations will be coded to prevent unintentional disclosure of enterprise-specific soil and crop information.

Monitoring began in the fall of 2003 and was repeated in the spring of 2004. Financial support for the AMPP monitoring has been secured for the first three years (e.g. through the fall of 2005). Funding will be sought from appropriate sources for longer term monitoring subject to maintaining a reasonable number of participating landowners in the monitoring program.

AMPP results

Irrigation water quality

The Tongue River is high quality irrigation water with its source as snowmelt in the Big Horn Mountains of Wyoming. The Tongue River Reservoir can store up to 79,000 acre-feet of water for irrigation. Water quality monitoring on the lower Tongue River at Brandenburg Bridge shows that water has met the new irrigation water quality standards during the irrigation season. There has been no measurable change in the EC and SAR of Tongue River water since CBNG development began in the basin in 1999 (**Figure 2**). Tongue River water is suitable for all forms of irrigation and has no salinity or sodicity limitations according to commonly used irrigation water quality criteria (Hanson and others, 1999).

Irrigated soil characteristics

Soils irrigated with Tongue River water fall into three main categories: floodplain soils that border the Tongue River in a 0.5 to 2 mile wide swath, flat-lying soils on river terraces, and relatively flat soils in the Yellowstone River floodplain in the T&Y Irrigation District. The T&Y Diversion Dam located 12 miles from the mouth of the river generally diverts one-half or more of

Table 3. List of extractions and analytical procedures used for the Tongue River samples.

Analyte	Extraction	Analytical Method see below	Units Comments	Field Replicates Relative Percent Difference [8]
Sample Preparation - Air dry or oven dry to constant weight at not more than 50 Celsius and report air dry water content on weight basis. Grind sample in flail type laboratory mill and sieve through ASTM #10, 2mm sieve and report coarse fragment weight percentage. Use riffle type splitter to obtain subsamples.				
pH	Saturation extract [5]	9040 [4]	Standard units	2.90%
EC	Saturation extract [5]	D1125-95A [6]	µsiemens/cm	17.60%
Soluble calcium	Saturation extract [5]	200.7 [2]	meq/L	23.40%
Soluble magnesium	Saturation extract [5]	200.7 [2]	meq/L	24.50%
Soluble sodium	Saturation extract [5]	200.7 [2]	meq/L	17.80%
SAR	NA	NA	Calculation -(Na/((Ca+Mg))^.5, ions in meq/L	15.70%
Chloride	Saturation extract [5]	300.0 [2]	mg/L	45.90%
Saturation percentage	Saturation extract [5]	Oven dry	Weight %, oven dry basis	4.00%
CEC	8-3: CEC or arid soils [5]	200.7 [2]	meq/100g	12.30%
ESP	13-3.3.1: Ammonium acetate extract [5]	200.7 [2]	Calculation – (NH_4OAc Extr Na - soluble Na)/CEC, in meq/100g	31.90%
texture	Mechanical analysis by hydrometer [5]	Oven dry	8-hr hydrometer method for clay, Weight %, oven dry basis	Sand 16.2 % Silt 7.0 % Clay 11.4 %
Alkalinity	Saturation extract [5]	2320B [7]		27.70%
Lime (%)	Lime [5] or suitable alternate method		Weight %, oven dry basis	
Nitrate as N	Saturation extract [5]	353.2 [3]	mg/kg soil	67.10%
Sulfate	Saturation extract [5]	200.7 [2]	meq/L	27.10%
Organic matter	Walkley Black [5]	NA	Weight %, oven dry basis	-
Phosphorus	24-5.4|: Olson (sodium bicarbonate) [5]	200.7 [2]	mg/kg soil	-
Potassium	13-3.3.1: Ammonium bicarbonate [5]	NA	mg/kg soil	-
Zinc	19-3.3: DTPA [5]	200.7 [2]	mg/kg soil	-
Barium	Hot water extract [5]	200.7 [2]	mg/kg soil	22.20%
Boron	Hot water extract [5]	200.7 [2]	mg/kg soil	7.20%
Fluoride	Hot water extract [5]	4110 B [7] or 300.0 [3]	mg/kg soil	13.10%
Selenium	Hot water extract [5]	200.8 [2]	mg/kg soil	20.90%
Clay mineralogy	NA	NA	Prepare 25 g split sample for submission to outside laboratory	NA

1 – from Methods for Chemical Analysis of Water and Wastes. 1979. (EPA/600/4-79/020)

2 - Methods for the Determination of Metals in Environmental Samples Supplement 1. 1994. (EPA/600/R-94/111)

3 - Methods for the Determination of Inorganic Substances in Environmental Samples (EPA/600/R-93/100)

4 – Test Methods for Evaluating Solid Wastes – Chemical and Physical Methods. EPA SW-846

5 – Agronomy Monograph Number 9 (19XX)

6 - Annual Book of ASTM Standards, Vols. 11.01 and 11.02

7 - Standard Methods for the Examination of Water and Wastewater, 18th, 19th & 20th Editions

8 – The quality assurance control limit for field replicates was 30 % RPD and is based on spring 2004 sampling

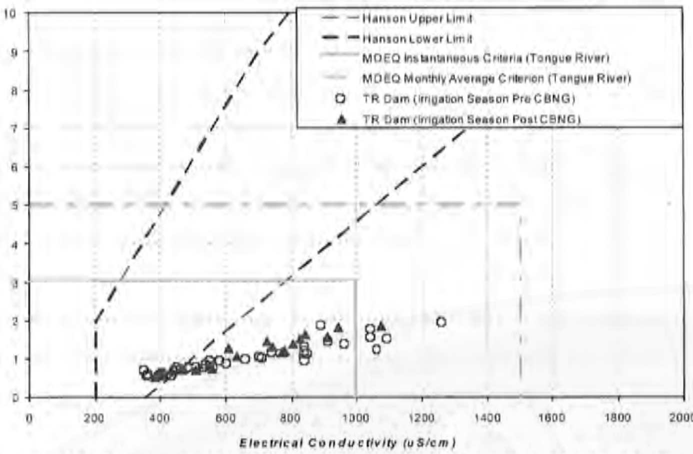

Figure 2. Tongue River water quality and standards.

the irrigation water used, and often reduces flow in the Tongue River near Miles City to less than 20 cubic feet per second (cfs).

All soils are formed from a mixture of alluvial parent materials, mostly derived from the sedimentary rocks of the Fort Union Formation. Soils have little profile development and generally lack argillic horizons owing to their fluvial origin. Although individual horizons may vary in texture from loamy sand to clay, the predominant soil texture is fine-loamy. There is no trend in soil texture evident from the headwaters to the mouth of the Tongue River. Clay mineralogy is mixed with about equal portions of kaolinite, illite, and smectite in most soils, reflecting the parent material influence (**Figure 3**). Consequently, irrigated soils should not be highly sensitive to dispersion by high sodium levels in irrigation water (Hanson and others, 1999), owing to the loamy soil textures and the sub-dominance of smectite clay.

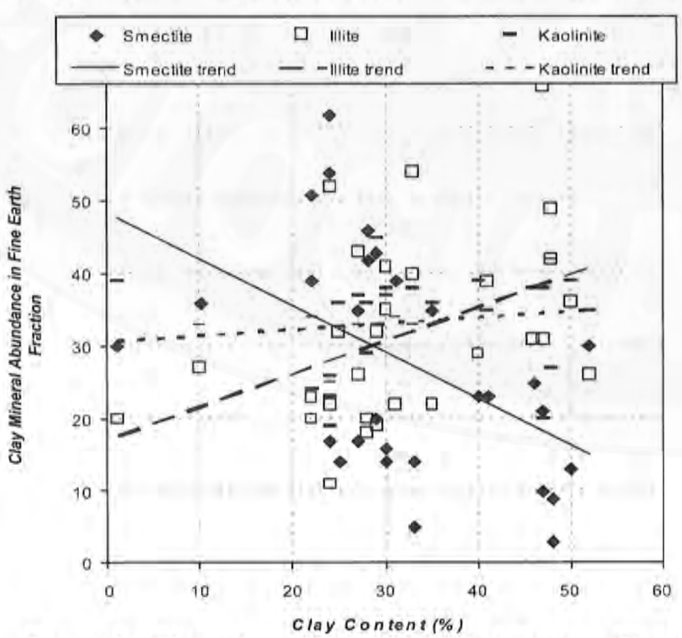

Figure 3. Clay mineralogy of irrigated Tongue River soils.

Salinity and leaching fraction

The fall 2003 and spring 2004 AMPP samples provide a measure of background characteristics of soils irrigated with Tongue River water. Despite the relatively homogeneous soils found in the basin, the EC levels were variable between sites reflecting a wide range of irrigation management. While flood irrigation is the predominant management approach in the Tongue River, sprinkler irrigation with side-roll systems is also commonly employed. Terrace soils are increasingly irrigated with center-pivot systems, especially in the middle to lower portions of the Tongue River between Brandenburg Bridge and the 12-mile Diversion Dam.

DeMooy and Franklin (1977) studied the irrigation water use and soil salinity patterns in Powder River soils and found four distinctive patterns of EC with depth in the soil profile. Each EC pattern is indicative of specific water management or drainage conditions. The following classification was adapted from their observations (**Figure 4**).

1. Soils that have elevated EC, with maximum EC at the soil surface. These soils typically have a high water table and are poorly suited for irrigation without improved drainage. These soils were not identified in the AMPP study.
2. Soils in which the EC approximates the irrigation water source near the surface, and which increases to a maximum at the base of the root zone. These are properly managed soils in which deep percolation occurs and maintains a salt balance in the profile.
3. Soils that have a low EC near surface, which increases to a maximum value within the lower portion of the root zone, generally at 24 to 36 inches, and then declines at the base of the root zone. In these soils, the irrigation management has changed so that less leaching has occurred in recent years than in the long-term. This could be due to a change in irrigation method (e.g. transition from flood to sprinkler), or restricted water availability (e.g. drought).
4. Soils with a low EC throughout the profile. Typically, these soils have been strongly leached and have a high leaching fraction.

Despite homogeneous soil texture and irrigation water quality, the EC measured in irrigated Tongue

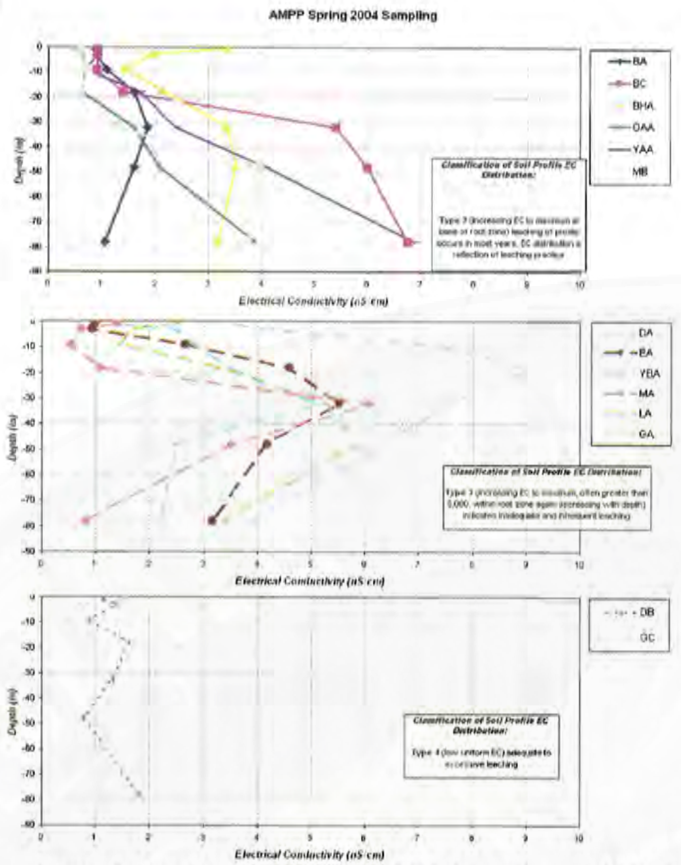

Figure 4. Depth distribution of EC in selected AMPP soils showing type 2 (above), type 3 (middle) and type 4 (below) distributions at various locations.

River soils varies from less than one to over 7 µS/cm. Higher EC levels were typically found from 36 to greater than 60 inches in depth. Irrigated crops typically respond to a depth-weighted average of the salinity within the root zone. For example, Hanson and others (1999) suggested that the average salinity of soil water taken up by crops can be estimated by using 40%, 30%, 20%, and 10% weighting from the upper to lower root zone quartiles (**Table 4**). Average root zone salinity (assuming a 48 inch root zone) ranges from less than 1 to 3.6 µS/cm, and averages 2.4 µS/cm in irrigated Tongue River soils. Average root zone salinity was slightly higher in the reference sites. Differences in average root zone salinity are attributed to modest differences in soil texture and discrepancies in irrigation management, especially the leaching fraction.

Leaching fraction (**Figure 5**) was calculated for each irrigated soil by comparing the EC of soil water in the 60 to 96 inch depth to the average irrigation water salinity, estimated to be 700 µS/cm during the growing season (Frankel, 1984; equation [1]). The EC of interstitial soil water (e.g. at field capacity) is indicative of the quality of deep drainage from irrigated soils. The soil EC is normally measured in a saturation extract, which is conducted at a higher water content. The EC of soil water (or drainage water) can be estimated by adjusting for differences in water content between the saturation percentage and field capacity (equation [2]). Field capacity for each AMPP soil was estimated from the soil texture.

[1]

$$LF = \frac{EC_i}{EC_d}$$, *where EC_i is the EC of irrigation water, and EC_d is EC of drainage*

[2]

$$EC_d = EC_e \, x \, \frac{\Theta_s}{\Theta_{fc}}$$, *where EC_e is the EC of a paste extract, Θ_s is the saturation percentage and Θ_{fc} is the field capacity estimated from soil water characteristic curves inferred from texture*

The average salinity of crop water uptake can also be estimated from the leaching fraction and from the irrigation water quality. Two approaches (Rhoades and Merrill, equation [3], and Bernstein and Francois, equation [4]) were used to determine the average salinity based on leaching fraction (Frankel, 1984). The average salinity calculated from the leaching fraction was lower than the weighted root zone salinity, mostly due to recent management changes in some soils (e.g. Type 3 EC distribution, **Figure** 4) that resulted in salt accumulation in the middle root zone. When these soils are returned to their conventional long-term management, the average salinity in Tongue River soils should decrease to 1.7 to 1.8 µS/cm.

$$\overline{EC_e} = 0.2EC_i\left[1 + \frac{1}{LF}\right] \qquad [3]$$

$$\overline{C} = \left[\frac{C_i}{(1\text{-}LF)}\right]\ln\left(\frac{1}{LF}\right) \qquad [4]$$

Sodicity and intake rate

The sodium adsorption ratio (SAR) and exchangeable sodium percentage (ESP) of the surface horizons of AMPP soils averaged 0.9 and 1.9, respectively, and was slightly higher for reference sites (**Table 5**). The SAR and ESP of deeper soil horizons, was higher than at surface, as expected due to increased salinity of the deeper layers. The intake rates were suitable for irriga-

Table 4. Salinity and leaching fraction of AMPP study sites.

Location	Water Source	Irrigation Method	EC Type Distribution	Weighted Root Zone EC	Mean EC_e Rhoades and Merrill	Mean EC Bernstein	Leaching Fraction
BA	Tongue	Flood	2	1.4	0.8	1.4	22%
BC	Tongue	Flood	2	2.5	3.2	2.3	5%
BD	Tongue	Dryland	NA	2.2	1.9	1.9	8%
DA	Tongue	Dryland --> Pivot	3	7.2	1.9	1.9	8%
DB	Tongue	Pivot	4	1.3	1.3	1.7	12%
EA	Tongue	Flood	3	3.6	1.6	1.8	10%
GA	Tongue	Side-roll	3	2.8	1.5	1.8	10%
GB	Tongue	Dryland	NA	3.3	1.9	1.9	8%
GC	Tongue	Flood	4	0.7	0.4	1	50%
LA	Tongue	Side-roll	3	3.3	2.8	2.2	5%
MA	Tongue	Pivot	3	2.1	0.6	1.2	28%
YAA	Tongue	Flood	2	1.7	3.2	2.3	5%
MB	Prairie Dog	Side-roll	2	1.1	2	1.9	8%
OAA	Otter	Flood	2	1	1.4	1.7	11%
Tongue River Average				**2.4**	**1.7**	**1.8**	**13%**
YBA	Yellowstone	Flood	3	3.4	0.9	1.5	18%
BHAA	Big Horn	Flood	2	2.3	1.7	1.8	9%
Reference Site Average				**2.9**	**1.3**	**1.7**	**13%**

Table 5. Sodium levels and intake rate for AMPP study sites.

Location	Water Source	Irrigation Method	Surface SAR	Surface ESP (%)	Deep SAR	Deep ESP (%)	Intake Rate (in/hr)
BA	Tongue	Flood	0.8	1.6	2	4.3	0.57
BC	Tongue	Flood	1.7	1.9	5.2	6.1	0.34
BD	Tongue	Dryland	0.6	1.2	5	4.6	0.51
DA	Tongue	Dryland --> Pivot	2.3	3.6	10	17	1.11
DB	Tongue	Pivot	0.9	2.2	2	5.7	1.07
EA	Tongue	Flood	0.9	1.5	4.4	6.4	0.46
GA	Tongue	Side-roll	0.6	2.1	6.5	6.2	0.87
GB	Tongue	Dryland	0.4	1	6.2	6.8	1.22
GC	Tongue	Flood	0.7	1.6	1.2	3.6	0.45
LA	Tongue	Side-roll	0.6	1.6	6.4	6.4	0.94
MA	Tongue	Pivot	0.7	1.8	3	3.5	1.86
YAA	Tongue	Flood	1.3	2.3	6	7.4	1.31
MB	Prairie Dog	Side-roll	0.6	1.8	2.8	4.4	3.37
OAA	Otter	Flood	0.4	2.2	2.8	6	0.87
Average Tongue River			**0.9**	**1.9**	**4.5**	**6.3**	**1.1**
YBA	Yellowstone	Flood	1.6	2	5.8	9	1.02
BHAA	Big Horn	Flood	3.8	2.8	1.8	3.1	0.86
Average Reference Sites			**2.7**	**2.4**	**3.8**	**6.1**	**0.9**

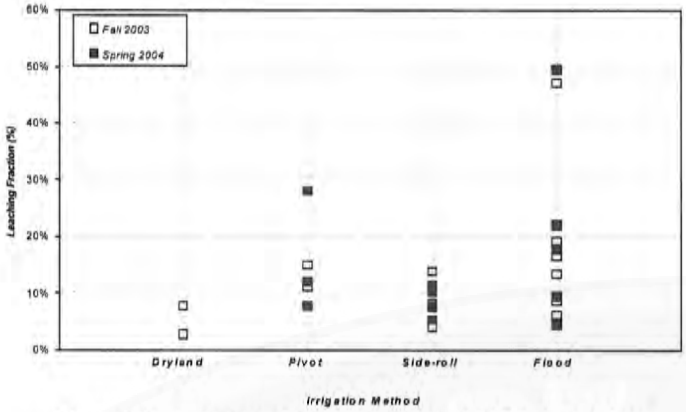

Figure 5. Average Tongue River AMPP leaching fraction by irrigation management method.

tion (NRCS 1997), ranging from 0.3 to over 3.0 inches per year, and averaging 1.1 inches per hour.

The correlation between SAR and ESP (**Figure 6**) in AMPP soils was somewhat variable, iwht an R^2 of 0.68, but had a slope similar to that found by the U.S. Salinity Lab (USDA, 1954).

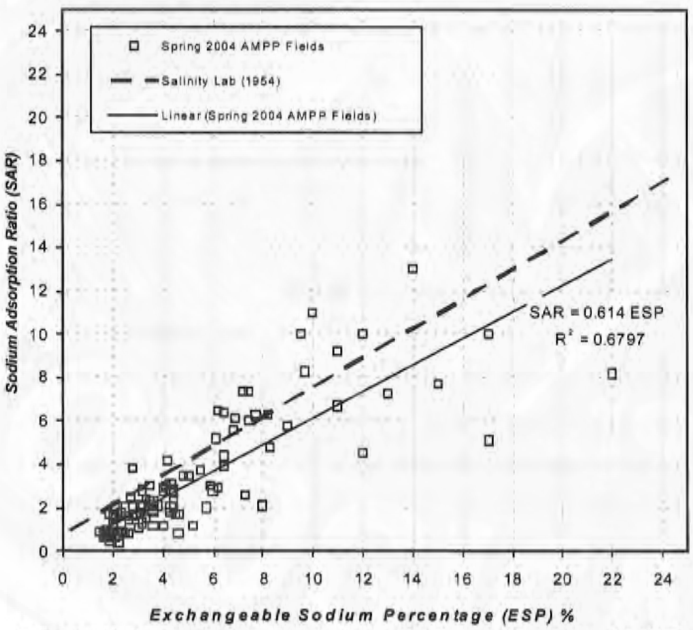

Figure 6. Correlation between SAR and ESP in AMPP soils.

Trends in soil chemistry

The ultimate objective of the AMPP sampling is to monitor long-term soil chemical trends. Long-term soil chemical trends, used in concert with water quality monitoring and crop yield determination, can help identify whether CBNG development is causing any deleterious effects on irrigated soils. As expected, little change in average EC (**Figure 7**) or surface ESP (**Figure 8**) occurred

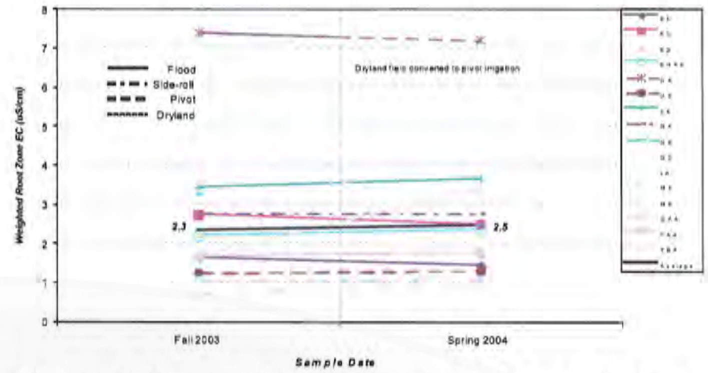

Figure 7. Depth weighted root zone EC trend Tongue River AMPP soils.

between the fall of 200 and spring 2004. The only exception was a substantial decrease in ESP and EC that occurred at site DA, which is a new irrigated field that was non-irrigated until late 2004.

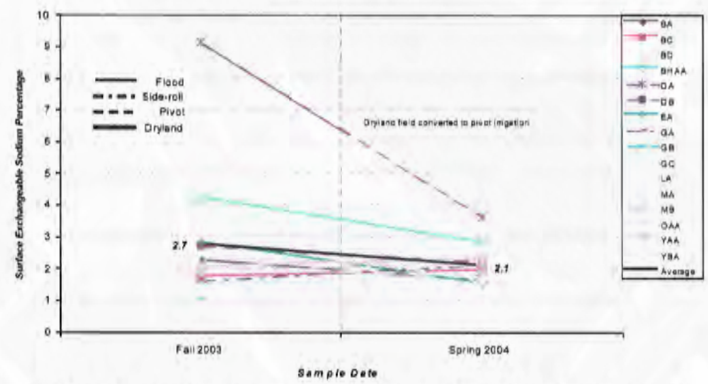

Figure 8. Trend in surface ESP in Tongue River AMPP soils.

Discussion and conclusions

- The Tongue River Agronomic Monitoring and Protection Program is an industry supported monitoring program designed to complement water quality monitoring;
- A basin-wide soil monitoring program must account for a number of issues:
  - Soil EC, sodium levels and other properties vary by depth, laterally, and seasonally;
  - Samples should be collected from a wide range of soils distributed across the river basin;
  - Sampling should occur at the same time of year;
  - Samples should be collected at the same depths using the same sampling protocols;

- Requires consistent methods of laboratory analysis;
- The Tongue River provides an important source of quality irrigation water in southeastern Montana;
- Stringent water quality standards were adopted by the State of Montana to protect irrigation water resources;
- Characteristics of irrigated Tongue River soils reflect the high quality water source and have no impairments due to EC or ESP; and
- Future AMPP monitoring results can detect trends in irrigated soil chemistry.

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Coalbed methane impoundments, mosquitoes, and West Nile Virus: An emerging problem?

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Emerging infectious diseases represent health-related and economic threats to human, livestock, and wildlife populations (Daszak and others, 2000). The rapid spread of West Nile Virus (WNV) across North America since its detection in New York in 1999 has resulted in widespread exposure among human, equine, and avian populations, with resulting morbidity and mortality (CDC, 2004). In 2003, the death and confirmed infection with WNV of greater sage-grouse, *Centrocercus urophasianus* in the Powder River Basin (PRB) (Naugle and others, 2004) prompted a need for information concerning mosquito vectors of WNV in the sagebrush steppe community of the northern PRB of north central Wyoming. The presence of surface water impoundments associated with coalbed methane (CBM) development in this arid region was recognized as a potential source of mosquitoes and other insects that might be involved in transmitting WNV and other arboviruses. The following information concerning insect potential vectors of WNV in the PRB and their infection with WNV was developed during August and September 2003.

Mosquito sampling

Mosquito populations were sampled using a blacklight/suction type trap supplemented with release of carbon dioxide gas (CO_2) as an attractant; this method is a standard procedure for mosquito arbovirus investigations (CDC, 2003). Light traps were set at 21 CBM impoundments during the months of August and September 2003. Sample sites were associated with areas of sage-grouse population monitoring in north central Wyoming and southern Montana. The traps were activated at dusk and harvested the next morning; captured insects were anesthetized, quick frozen on dry ice, and stored at -80° C.

WNV assay

Female mosquitoes and biting midges were sorted to species on liquid nitrogen and grouped in pools of either 20 or 50 specimens (mosquitoes and biting midges, respectively). West Nile Virus RNA was extracted from pooled insects with an RNeasy 96 kit, and then processed using the TaqMan one Step RT-PCR master mix reagents. The "WNVENV" and "WN3'NC" primers/ probes were synthesized according to Lanciotti and Kerst (2001). Pool extracts were processed by RT-PCR, with pools considered positive when CT values were $<$ 37, and the normalized fluorescent signal (Rn) was 2 X $>$ than the average of eight non-template controls for both primer/probe sets. Infection rates were calculated by the method of Biggerstaff (2003).

Results mosquito sampling

Mosquitoes belonging to four genera were captured. Of these, *Culex tarsalis* was most common and abundant, followed by lesser numbers of *Ochlerotatus dorsalis, O. melanimon* and other western species. *Culex* *tarsalis* was captured at 15 of 21 sample sites. The biting midge, *Culicoides sonorensis*, was captured at 3 sites.

Results insect assay for WNV

Table 1 summarizes the results of testing mosquitoes and biting midges for WNV. A total of 101 pools (1774 specimens) of *C. tarsalis* (20 females per pool) were tested, of which 12 pools (11.9 %) were positive for WNV. The infection rate for *C. tarsalis* was 7.16/1000. Nineteen pools (903 specimens) of *C. sonorensis* were tested, of which two pools (2.2 %) were positive for WNV. The infection rate in *C. sonorensis* was 2.31/1000.

Discussion

This study demonstrates several points of concern regarding the potential for WNV transmission among vertebrates associated with the sagebrush steppe community of the northern PRB. First, the mosquito *C. tarsalis* was common and abundant at surface water impoundments associated with CBM development in the northern PRB. Second, WNV was detected in *C. tarsalis* from several locations within the PRB. This mosquito species is known to be an efficient vector of WNV (Goddard and others, 2002) and, as a species that feeds from birds (Reisen and Reeves, 1990), a probable vector of WNV among sage-grouse and other avian species. Because *C. tarsalis* readily exploits a variety to standing water sources for larval development, also feeds from mammals, and is widely distributed throughout western North America (Reisen and Reeves, 1990), it also is likely the primary vector of WNV among both birds and mammals in the intermountain West.

The detection of WNV in the biting midge, *Culicoides sonorensis*, was unexpected. This species is known to transmit several arboviruses that cause diseases of livestock (Mellor and others, 2000), but it has not been associated with WNV or related arboviruses (Karabatsos, 1985). The detection of WNV in this insect raises additional questions because this species is considered to largely blood-feed from mammal hosts. Since WNV circulates among avian populations that amplify viruses (Komar and others, 2003), the source of WNV in *Cu. sonorensis* raises the question of where the virus was acquired.

Table 1. West Nile virus infection rates in mosquitoes and biting midges from the northern Powder River Basin, 2003.

Sample location	Mosquito *Culex tarsalis*	Biting midge *Culicoides sonorensis*	No. specimens tested	No. Pools tested	No. pools positive for WNV* (RT-PCR test)
1	X		146	8	3
2	X		58	4	1
3	X		487	25	1
4	X		38	3	0
5	X		32	2	0
6	X		587	30	2
7	X		21	2	0
8	X		6	1	0
9	X		27	2	0
10	X		4	1	0
11	X		12	1	1
12	X		1	1	0
13	X		171	10	2
14	X		64	5	0
15	X		120	6	2
16		X	100	2	0
17		X	3	1	0
18		X	800	16	2

* WNV infection rate *Culex tarsalis*: 11.9 % of pools; 7.16/1000.

WNV infection rate *Culicoides sonorensis*: 22.2 % of pools; 2.31/1000.

As concerns the detection of WNV in both *C. tarsalis* and *Cu. sonorensis*, it should be noted that detection of the virus in field-captured insects does not necessarily imply that either species transmits WNV to sage-grouse or other animals. The implication of an insect species as a vector of a pathogen requires additional ecological and experimental information before vector status can be accepted (Barnett, 1960). Research to develop this information is in progress.

This study demonstrates the presence of insects, particularly the mosquito *Culex tarsalis*, in the sagebrush steppe community with CBM development that have potential for transmitting WNV among wildlife, livestock, and human populations. The construction of additional CBM impoundments can be expected to provide additional habitat for larval mosquitoes unless the conditions that support larval development are reduced or eliminated. Whether or not WNV evolves into quiescence or remains a perennial problem in the intermountain West remains to be determined.

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Powder River Basin wildlife research, monitoring, and protection

Thomas Bills, Wildlife Biologist–U.S. Bureau of Land Management, Buffalo Field Office, Buffalo, Wyoming

Wildlife is an important and integral part of the Powder River Basin (PRB) landscape. Many agencies [U.S. Bureau of Land Management (BLM), U.S. Fish and Wildlife Service, U.S. Bureau of Indian Affairs (BIA), USDA Forest Service (USDAFS), and state wildlife departments] share responsibilities for wildlife conservation and protection; many of these agencies also play a role, directly or indirectly, in coalbed natural gas (CBNG) development. These agencies and additional federal and state agencies formed the Coalbed Natural Gas Interagency Working Group. The working group's mission is to work together to protect the air, water, land, fish, wildlife, and plants in the PRB for current and future generations while providing for natural gas development to address the nation's energy needs. The working group formed taskforces for the individual resources.

This paper will summarize actions the wildlife taskforce is undertaking to inventory, protect, monitor, and research wildlife resources within the PRB at the project and basin scales. The paper will be inclusive of the entire Powder River Basin, located in Montana and Wyoming, and all agencies. Some individual species and species groups of interest include: Threatened and Endangered Species (bald eagle, black-footed ferret, Ute ladies'-tresses orchid), sensitive species (black-tailed prairie dog, greater sage-grouse, ferruginous hawk, burrowing owl), small mammals, migratory birds, reptiles, and amphibians.

Project scale inventory, protection, and monitoring

Our primary objective at the project scale is to encourage operators to perform habitat assessments and wildlife inventories early in their planning process so that projects may be designed with the least impact to the operator and wildlife. The timeline for this process is as follows:

1. Operators submit annual work plans including habitat assessments and wildlife inventory/protection plans in autumn. This should occur prior to Notice of Staking (NOS) and/or Application for Permit to Drill (APD) submission.
2. BLM/USDAFS provide operators with a list of required and recommended wildlife inventories.
3. Operators plan and submit projects (NOS/APDs) with wildlife protection incorporated.
4. BLM/USDAFS analyze and permit CBNG projects, which include wildlife protection.
5. Occupied habitat is monitored for five years to evaluate CBNG development effects.

The wildlife taskforce sponsors two meetings annually with CBNG operators and their private wildlife consultants to insure coordination and consistency.

1. At an autumn meeting, the taskforce presents the previous year's inventory and monitoring results and discusses any concerns identified during the previous year.
2. At an early spring meeting, the taskforce presents survey protocols, identifying any modifications, and facilitates coordination of the current year's inventory and monitoring efforts.

Basin scale inventory, protection, and monitoring

Our primary objective is to identify and coordinate inventory, monitoring, and research efforts across the PRB. The wildlife taskforce meets several times annually to accomplish this objective.

At the basin scale, we are concentrated on populations and their habitat across the landscape. Examples of population inventory and monitoring include: surveys to identify raptor nest sites, or annual surveys of known sage-grouse leks. We are analyzing satellite imagery to inventory and monitor habitat across the basin. With the imagery, we can identify and model suitable habitat. We can also monitor changes to the landscape such as the development of CBNG resources and wildlife habitat fragmentation. The taskforce intends to monitor the land cover change every two years. The taskforce has prepared a monitoring plan that details the proposed monitoring effort for each species and the landscape monitoring. The plan is available from the BLM Buffalo Field Office.

Research projects

The wildlife taskforce is also working to coordinate research efforts. Examples of current and proposed research are as follows:

- Current or recent studies: greater sage-grouse (BLM, Wyoming Game and Fish Department, Montana Fish, Wildlife & Parks, University of Montana, Montana State University, University of Wyoming) ferruginous hawk (TBNG), burrowing owl (TBNG), mule deer (BLM-Miles City, BIA), migratory birds (BLM-Miles City), amphibians (BLM-Miles City);
- Planned research: mountain plover (BLM Buffalo), ferruginous hawk and golden eagle (BLM-Buffalo), big game (BLM-Buffalo), small mammal (BLM).

Summaries of the current and proposed research are included in the taskforce monitoring plan.

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CONCURRENT SESSION—Session 4: Information management, risk assessment and legal issues—Wyoming Union, Family Room

Co-Chairs: Gary Beach, Wyoming Department of Environmental Quality and Jeff Hamerlinck, Wyoming Geographic Information Science Center

1:30 p.m.	Western resources project: Collaborative effort to address water issues in the Powder River Basin–*Britt Dearman, Apache Corporation & Western Resources Project*
1:50 p.m.	Overview of an interactive geologic, hydrologic and water quality database and model for the northern Powder River Basin–*Nick Jones, Wyoming State Geological Survey*
2:10 p.m.	The components and functionality of the CBM Clearinghouse–*Jim Oakleaf, Wyoming Geographic Information Science Center*
2:30 p.m.	Information management innovations in Wyoming federal/state governments–*Larry Biggio, State CIO; Gary Beach, Wyoming Dept. of Environmental Quality; Jim Gazewood, U.S. Bureau of Land Management; Traci Lindsten, Wyoming State Engineer's Office; Rick Marvel, Wyoming Oil and Gas Conservation Commission*
2:50 p.m.	BREAK
3:20 p.m.	Total maximum daily load (TMDL) development for the Tongue and Powder River basins in Montana–*Dan Hengel, Wyoming Department of Environmental Quality*
3:40 p.m.	Procedure for determining the risk of exceeding groundwater standards at prospective CBNG impoundment sites–*Arthur O'Hayre, Applied Hydrology Associates, Inc.; Michael Day, Applied Hydrology Associates, Inc.*
4:00 p.m.	Policy decisions and management tools needed for an aquatic risk assessment of coalbed natural gas product waters–*Joseph S. Meyer, University of Wyoming; M.B. Forbes, University of Wyoming; S.J. Clearwater, National Institute of Water and Atmospheric Research Ltd.*
4:20 p.m.	Easy money, hidden costs: Applying precautionary economic analysis to coalbed methane in the Powder River Basin–*Joshua Skov, Science and Environmental Health Network; Nancy Myers, Science and Environmental Health Network*
4:40 p.m.	*Water as a waste: Coalbed methane and the Clean Water Act–*Traci L. Garrett, University of Wyoming*

*Written paper was not available for this volume

Western resources project: Collaborative effort to address water issues in the Powder River Basin

Britt Dearman–Apache Corporation, Houston, Texas

The Western Resources Project Foundation (WRP) was established in 2001 to fund peer-reviewed university research focused on water resources and coalbed methane (CBM) development in the Powder River Basin (PRB). Apache Corporation, ConocoPhillips, and Marathon Oil Corporation contributed funds to initiate the research.

Two field sites were chosen in 2002 to conduct a complement suite of research: one on Beaver Creek located southwest of Gillette, Wyoming, operated by ConocoPhillips and one at the Ucross Ranch located southeast of Sheridan, Wyoming, operated by Wolverine Operations. The Beaver Creek site consists of on-channel ponds on an ephemeral stream and the Ucross Ranch site consists of an off-channel pond near a perennial stream. The sites are equipped with shallow and deep monitoring wells, stream gauges, and meteorological instruments. Installation of field instrumentation and initial baseline measurements began in the summer of 2002. In addition to the data gathered at the two sites, several CBM operators contributed data from over 500 producing wells.

The research will enhance the understanding of water flow mechanisms and geochemical interaction of CBM produced water with ground and surface water. The data will be used to calibrate hydrogeologic models that can be used to forecast the fate and transport of produced water. Additional studies include CBM well completion methods, injection feasibility, gas migration within coal reservoirs, and irrigation methods. The collaboration among industry participants and investigators is yielding results that can be applied to both CBM development and water resource enhancements.

The focus of the hydrology studies is to understand the impacts of CBM development on shallow and deep aquifer systems and the subsequent impact of these hydrologic systems on surface water hydrology. Dr. Demian Saffer (University of Wyoming) is studying the "fate and transport" concept of CBM produced water from its conception at the CBM well and its conveyance through the geologic system. This study is evaluating the hydrologic system as CBM produced water flows through in-channel impoundments via ephemeral streams. Off-channel impoundments used for the storage, infiltration, and evaporation of produced water are also included. This work will address the nature, distribution, and rates of conveyance losses and the impact that surficial geology has on the hydrologic system. As CBM produced water moves through the system the water quality of the ground water and surface water resources is impacted. The nature of this impact is addressed through studies conducted by Dr. Carol Frost (University of Wyoming) and Mr. John Wheaton (Montana Bureau of Mines and Geology). Dr. Frost is evaluating the Sr isotope as a tracer to determine the fate of ground water pumped from the various coal seams. An evaluation will be made using the Sr isotope to trace the fate of CBM produced water on surface water and on shallow aquifers. In addition, this technique will assess the possibility of aquifer leakage due to potentiometric pressure reductions. An exploration of the possible reactions that may occur in the surface and ground water systems resulting from the discharge of produced water is being conducted by Mr. John Wheaton. An evaluation of the chemistry resulting from the interactions of CBM produced waters with surface water along reaches of streams is being assessed. In addition, the impact of produced water on the water quality of alluvial ground water either from stream channel infiltration or from holding impoundments continues to be evaluated.

The extraction of CBM requires the production of ground waters. Much of the ground waters produced have the characteristics of beneficial resources that can be used to improve rangeland plant production or to increase crop production. However, it is important that water applied to soils meets a favorable combination of salinity and sodicity that will allow the plants to grow at high production rates and that will maintain the structure of the soil. Dr. Terry Brown (Western Research Institute) is evaluating the impact of CBM produced water from coal seams in the Cooksley Ranch area on the chemical and physical properties of soils. Interactions between salinity and sodicity and other important parameters associated with soil aggregation are being evaluated to assess their impact on the soils found in the area. The use of soil amendments and water treatment are included in the study.

Methods of completing CBM wells can have a major impact on the ability to efficiently extract methane from coal seams. The goals of Dr. Zoback's study are to evaluate wellbore completion practices to determine if there are ways to produce less CBM water and still achieve adequate depressurization for production and to evaluate the feasibility of injection of CBM water as a cost effective water disposal process. This work will result in a better understanding of the mechanisms responsible for excessive water production from some wells in the PRB, and recommendations about changes to currently used completion techniques to remedy this problem. Additional work in the geophysical area was completed by Dr. Jerry Harris (Stanford University). Dr. Harris is using seismic methods to monitor the spatial and temporal evolution of methane production in the vicinity of producing wells. This work may provide information that can be used to optimize methane recovery by characterizing gas flow paths. This study will also shed light on the importance of two-phase flow studies to evaluate ground water production and ground water recharge evaluations.

Applied Hydrology Associates provided expertise to install hydrologic monitoring systems supporting the individual research projects. Their work aided in the development of high quality, "state of the art" facilities that will likely result in collection of appropriate data required to successfully complete the research activities outlined above.

Periodic presentations of this research have been made to industry and regulators to keep them apprised of the results of the project. Their feedback has helped focus the research on addressing critical issues associated with CBM production and water resource management. This project should assist industry and regulators in making important decisions about CBM development in the PRB based on good scientific investigation.

Overview of an interactive online Internet-based map server (IMS) of Wyoming's northern Powder River Basin

Nicholas R. Jones, GIT–Wyoming State Geological Survey, Laramie, Wyoming

Internet Map Server

The Northern Powder River Basin Hydrologic and Geologic Internet Map Server (IMS) contains geologic resource information for the northern part of Wyoming's Powder River Basin (PRB). The data used to generate the geologic framework was collected from geophysical well logs, resource and geologic maps, and various open file reports. The IMS is an interactive litho-stratigraphic model designed to provide information such as lithologic columns, cross sections, and plan view maps of 32 coal deposits within the Eocene Wasatch and Paleocene Fort Union formations. Well data was also used to discern the Wasatch-Fort Union contact, the KT boundary, the top of the Foxhills Sandstone, and the top of the Cretaceous Bear Paw/Pierre Shale. In addition to the litho-stratigraphic model, water quality data from wells was then crossed with the correlated coals in an effort to forecast future produced water quality within the basin. The IMS was generated as a predictive tool for developers, water users, gas producers, and regulators to more effectively estimate the quality of ground water prior to coalbed methane (CBM) production.

In addition to the geologic and water-quality components, the IMS also has a geographic component. This allows the user to set the base map, roads, rivers, county boundaries, well locations, water quality sample sites, and public land surveys according to the information required for their individual needs. The scale of the map may also be changed; users may also "Zoom" in or out to particular locations within the predefined project area.

The Northern Powder River Basin IMS is available via the internet and can be accessed from the following state agency websites: Wyoming Resource Data System, The Wyoming State Geological Survey, and the CBM Clearing House. There is no charge for the use of the IMS and is available to anyone with access to a computer that is connected to the internet.

Water quality information within the IMS

Information available in the IMS pertaining to water quality can be accessed in one of two ways. First, the user only needs to generate a lithologic column at a location of their choosing and then click on a coal, zone, or formation. This method provides the user with interpolated water quality values at that point and makes two types of water quality maps available. One map is a bubble plot and the other is an interpolated color-contour map. Both maps show the location and range of values for a particular constituent. This option for accessing water quality provides information on 11 different constituents including: calcium, chloride, carbonate, total dissolved solids, fluoride, bicarbonate, potassium, magnesium, sodium, sodium adsorption ratio, sulfate, and specific conductance.

The second option for acquiring water quality information is site specific. This method allows the user to select either a township or hydrologic unit within the project area. The results for these data are tabular and provide the user with all available water quality information for that area. The data may be viewed site by site or all data for all sites may be downloaded in comma separated files (CSV).

Accurate and consistent coal nomenclature

Accurate reporting of collected data and and a consistent use of coal nomenclature are extremely important. Due to the complex nature of coal deposits within the PRB, it is often difficult to associate producing beds of one name to another within the basin. One example that is commonly used is "Big George." Some investigators consider the Upper Wyodak and the Big George to be two separate and unique deposits. However, according to results generated from the litho-stratigraphic model, the two deposits are correlative and equal. **Figure 1** illustrates which coals coalesce to create both the Upper Wyodak and the "Big George." The "Big George" does not extend north to the Wyoming-Montana border as depicted by many CBM wells' reported producing zones. Instead, the term "Big George" is geographic in nature and is meant to denote the western part of the Wyodak coals in the shape of a giant foot-print within the center of the basin.

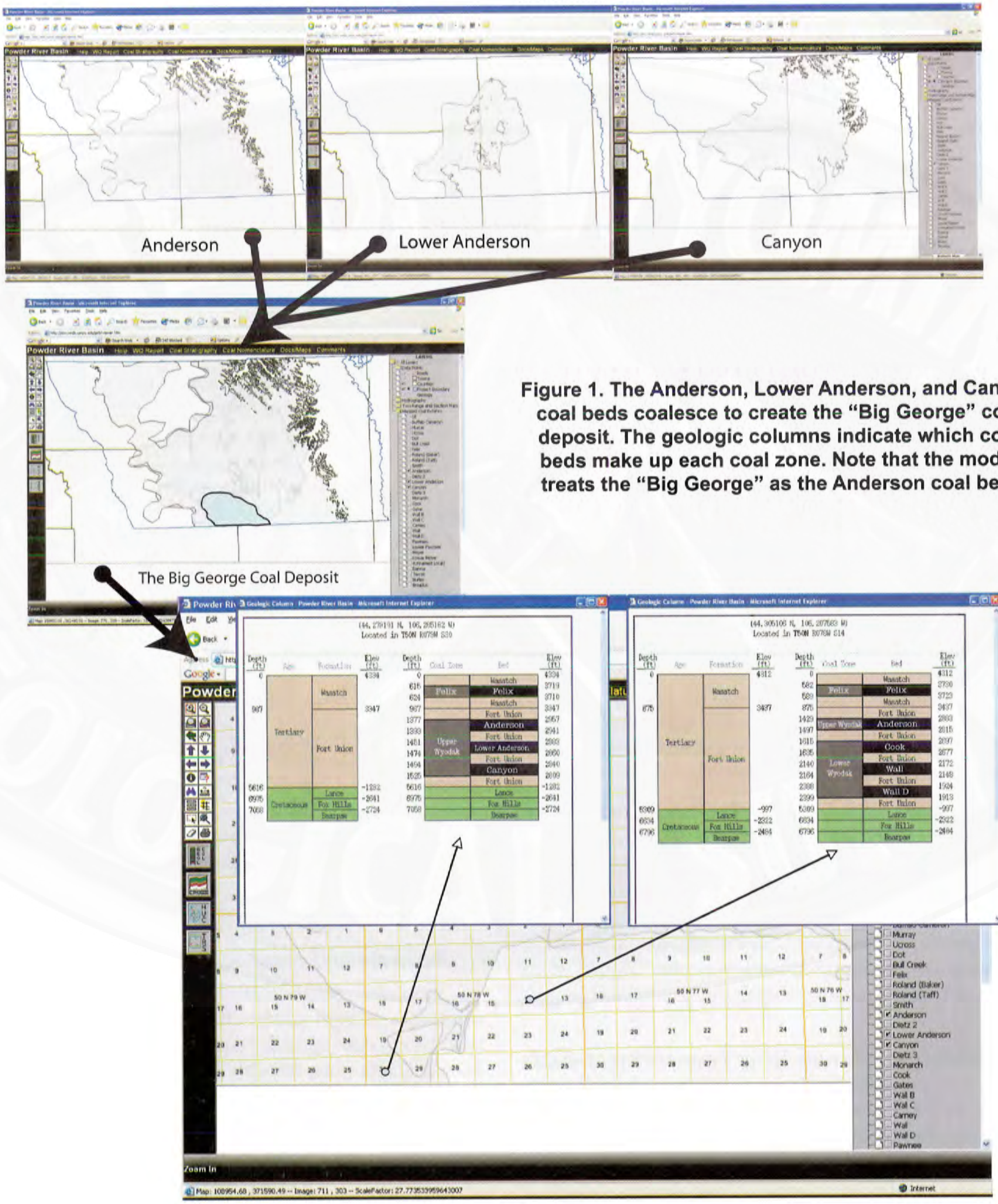

Figure 1. The Anderson, Lower Anderson, and Canyon coal beds coalesce to create the "Big George" coal deposit. The geologic columns indicate which coal beds make up each coal zone. Note that the model treats the "Big George" as the Anderson coal bed.

The components and functionality of the CBM Clearinghouse

Jim Oakleaf–Wyoming Geographic Information Science Center, University of Wyoming, Laramie, Wyoming

The Wyoming CBM Clearinghouse is a centralized Internet-based clearinghouse for textual, tabular, photographic, and spatially-referenced information pertaining to coalbed methane (CBM) resource development and related management issues in Wyoming. The Clearinghouse provides a single, up-to-date, and easy-to-use entry point for accessing data and information on all aspects of CBM-related issues in Wyoming. Target audiences include resource management agencies, industry, nongovernmental organizations, and the general public.

This presentation will provide users with an understanding of the components and functionality of the CBM Clearinghouse. A majority of the talk will focus on the Internet mapping application available through the Clearinghouse and how users can incorporate much of these data into their own desktop GIS software. Finally discussion will be directed toward future enhancements and improvements for the site.

Information management innovations in Wyoming federal/state governments

Larry Biggio–WyomingState Chief Information Officer, Cheyenne, Wyoming
Gary Beach–Wyoming Department of Environmental Quality, Cheyenne, Wyoming
Jim Gazewood–U.S. Bureau of Land Management, Cheyenne, Wyoming
Traci Lindsten–Wyoming State Engineer's Office, Cheyenne, Wyoming
Rick Marvel–Wyoming Oil and Gas Conservation Commission, Casper, Wyoming

Several state and federal government agencies are involved in information management efforts to strengthen and streamline oil and gas development in Wyoming. Wyoming's natural resource base is vast, providing jobs and revenues to governments at all levels. Potential growth in natural gas production, in particular, has the prospect of increasingly benefiting the federal, state, and local governments, as well as citizens of the state.

Two significant issues threaten to impair Wyoming from gaining the full potential growth and benefit associated with mineral development. First, regulatory inefficiencies can slow or even stall the pace of permitting and development of the mineral estate. Second, the resource must be developed by fully protecting Wyoming's environment, without jeopardizing agriculture or tourism.

Wyoming Governor Dave Freudenthal has initiated a collaborative process, working with industry, other stakeholders, and state and federal agencies, to develop a package of measures addressing these two problem areas. As currently perceived, the project will involve three phases and is expected to span a period of four years. Phase 1 will ensure state agencies have sufficient electronic databases to support the streamlined permitting processes. Phase 2 will allow the sharing of common data needed in the permitting process between participating state agencies, as well as the BLM. Phase 3, if approved, involves the building of the internet-based services to allow for the online application and tracking of permitting.

Common project goals include a mechanism to share data, reduce redundancy in data collection and hosting, increase reliability of data, assign responsibility for certain data, identify and use needed metadata, establish policy guidance useful in other energy development areas, identify any existing work that would add to the current project, and identify data that should be shared among the parties, as well as the purpose of that data and the level of accuracy required.

The state and federal agencies participating in the project include the Wyoming Department of Environmental Quality (DEQ), the Wyoming Oil and Gas Conservation Commission (WOGCC), the Wyoming State Engineer's Office (SEO), and the U.S. Bureau of Land Management (BLM).

State agencies are currently moving along parallel paths, which will converge with the development of common internet services available through a single point or service portal. Initial agency efforts include the new discharge monitoring reporting system (eDMR) and agency database consolidation at DEQ, digitizing historical and current water rights information at SEO, publishing data and an internet mapping service for use by staff and public at the WOGCC, and BLM's work to increase electronic permitting and reporting, increase collaboration with states, and build a data exchange framework with industry.

Services are available from the following sites:

- <http://wogccms.state.wy.us/ai_frameset.cfm>
- <http://seo.state.wy.us/cbm.aspx>

- <http://seo.state.wy.us/seo_deq_map.aspx>
- <http://www.wispermits.org>
- <http://deq.state.wy.us/wqd/index.asp?pageid=5>

If approved, the final stage of the project will be the development and implementation of internet based services for coalbed natural gas well permitting. These services will be accessible from a single site and address the requirements of the industry, the three primary state agencies, and the BLM. Common services will include items such as postings of all permitting requirements, checking completeness of applications, accepting and processing payments, routing information to appropriate agencies, maintaining status of applications, providing public access to data and management actions, etc.

The next steps in the project include obtaining needed funding, identifying stakeholders and resources, creating a unified business process and data sharing model, developing and adopting standards for presentation of data, identifying and establishing the technical infrastructure, creating a unified permitting application template, and integrating with Wyoming's EPortal.

Total Maximum Daily Load (TMDL) development for the Tongue and Powder River basins in Montana

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The Montana Department of Environmental Quality (MDEQ) is developing a Total Maximum Daily Load (TMDL), which includes allocation of specific water quality constituents to protect existing or designated uses in the Tongue and Powder River basins. The Wyoming Department of Environmental Quality (WDEQ) is cooperating, via frequent dialogue and modeling committee participation, with MDEQ in their TMDL process. Coalbed methane (CBM), or coalbed natural gas (CBNG), development and product water management in the Tongue and Powder River basins is a key component in the development of these TMDLs.

A synopsis of the process completed to date will be presented including schedule milestones, watershed model selection, data collection, model data gaps, source identification and source contributions, model calibration, and model simulations to predict assimilative capacity for identified constituents. In addition, alternative models (BSNMODX and Arc Hydro), and/or methodologies, for assessing water quality status will be discussed and compared to the TMDL model.

The development of these predictive models for the Tongue and Powder River basins will assist the WDEQ in the development and implementation of a watershed-based approach to issuing National Pollutant Discharge Elimination System (NPDES) permits.

Procedure for determining the risk of exceeding groundwater standards at prospective CBNG impoundment sites

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Based on preliminary monitoring results at coalbed natural gas produced water impoundments in the Powder River Basin, the Wyoming Department of Environmental Quality has developed and issued interim guidelines for compliance monitoring of unlined impoundments. Although Section 1 of these guidelines allows operators to provide documentation prior to discharge that the proposed unlined impoundment poses no threat of violation of groundwater standards, it provides no guidance or methodology for determining the risk of exceeding groundwater standards at a proposed pond location. This presentation describes a predictive procedure for determining whether seepage from a proposed impoundment presents a risk for exceeding state groundwater standards. The procedure requires saturated paste extract information from drill cuttings or core samples from the unsaturated zone in the vicinity of the proposed impoundment. The procedure has been developed and calibrated based on limited information from one off-channel impoundment site and will be refined and modified as additional information is obtained.

Policy decisions and management tools needed for an aquatic risk assessment of coalbed natural gas product waters

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Melanie B. Forbes–University of Wyoming, Laramie, Wyoming
Susan J. Clearwater–National Institute of Water and Atmospheric Research Ltd., New Zealand

Coal bed natural gas (CBNG) wells are rapidly being installed in Wyoming and other western states in the U.S. Sometimes, large amounts of CBNG product water are discharged into surface drainages (De Bruin and others, 2000). Therefore, an aquatic risk assessment of CBNG product waters is needed to address concerns about potential adverse effects of product waters (treated or untreated) to aquatic organisms. Herein we identify five major needs for a defensible aquatic risk assessment of those CBNG discharges.

The first need is well-identified goals and measurable objectives for surface waters in the region. This need is easy to state but will be difficult to accomplish given the wide range of species, habitats, interests, and perspectives involved. For example, some parties might be mainly interested in providing adequate habitat for trout populations, whereas other parties might be interested in ensuring adequate habitat for resident species of prairie rivers, such as sturgeon (*Scaphirhynchus sp.*) and native minnows (e.g., sturgeon chub -- *Macrohybopsis gelida*) in the Powder River. The habitat needs of some resident aquatic species in the prairie rivers will differ considerably from suitable trout habitat. Consensus will be needed among all interested parties about the goals and objectives before starting the risk assessment. The question is, who will lead this effort? A neutral party such as the Ruckelshaus Institute for Environment and Natural Resources might be well-suited for that task.

The second need is a model to predict the toxicity (i.e., the effects) of CBNG-related waters to aquatic life, to help decrease the time and expense of testing a large number of CBNG wells. Although toxicity testing of some CBNG-related waters is necessary, it can be time-consuming and moderately expensive when many samples must be processed. Instead, models calibrated to the toxicity of CBNG-related waters might be used to predict the toxicity of product waters to aquatic organisms and, thus, cost-effectively screen a large number of waters based on chemistry, identifying those that need confirmatory toxicity testing. Because this kind of approach could decrease time and costs for the CBNG industry, we evaluated the ability of a logistic regression model of the toxicity of major inorganic ions (Mount and others, 1997) to predict the acute toxicity of CBNG-related waters to two freshwater aquatic invertebrates (*Ceriodaphnia dubia* and *Daphnia magna*) and the fathead minnow (*Pimephales promelas*). For the majority of CBNG product waters and stream waters in which CBNG product water constituted the entire flow of the stream, the major-ion model consistently over-estimated mortality (see Forbes, 2003 for details of the methods and results). Therefore, the Mount and others (1997) model is "conservative" from a regulatory perspective and could be used as a first-tier test. However, a less over-protective model (i.e., a model that over-predicts mortality less than the Mount and others, 1997 model) would be cost-effective for industry and could still be environmentally protective.

The third need is a hydrology model to estimate the amount of CBNG-related water that is discharged into receiving waters (i.e., the exposure), either as a percentage of product water mixed into the receiving water (minimum needed output) or as changes in concentrations of major ions after mixing into the receiving water (preferable output of the model). This type of hydrology model would need to account for conveyance losses (evaporation and infiltration of water), mineral inputs from or losses to soils, seasonal variations in flow rates of receiving waters, and seasonal variations in chemistry of receiving waters. Without adequate hydrology models, results of toxicity tests, models of toxicity, or models of habitat suitability will be difficult to interpret in the context of CBNG discharges in the field.

The fourth need is a relatively sensitive salt-water tolerant organism for use in toxicity tests, because freshwater species traditionally approved for toxicity testing by regulatory agencies (e.g., *Ceriodaphnia dubia, Daphnia magna, Pimephales promelas,* and various trout species) do not tolerate high salinity–even though, for example, some of the receiving waters in the Powder River Basin (PRB) are relatively saline. In some situations, it would be more reasonable to use a salt-tolerant species instead of a salt-intolerant species in whole-effluent toxicity (WET) tests of CBNG product waters. Moreover, in some PRB drainages, the relatively dilute CBNG product waters will tend to "dilute" the relatively saline receiving waters (Clearwater and others, 2002). Because dilution of the receiving water might be detrimental to some resident species in the Powder River and other relatively saline receiving waters, use of a salt-tolerant species might again be more appropriate than a salt-intolerant species. However, we are unaware of a suitable species that is routinely used in aquatic toxicity testing.

The fifth need is laboratory- and field-based information about tolerances (including behavioral responses) of aquatic species and community assemblages to changes in (1) concentrations of major inorganic ions, and (2) seasonal patterns of temperature, water flow, and turbidity that will be caused by large-scale discharges of CBNG product waters. This is especially important for species assemblages that do not contain recreational or commercial fisheries (e.g., the Powder River), because very little is known about the habitat preferences of species in those communities. Additionally, in relatively saline receiving waters that might be "diluted" by CBNG product waters (e.g., the Belle Fourche River), the resistance of the fish and invertebrate communities to invasion by less salt-tolerant species is unknown. This constitutes a major knowledge gap for an aquatic risk assessment of CBNG production.

Acknowledgements

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Easy money, hidden costs: applying precautionary economic analysis to coalbed methane in the Powder River Basin

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The goal of economic analysis is to provide a sense of the net gain or loss to the commonwealth and access to questions of distribution (who pays, who gains). This analysis of coalbed methane (CBM) development is informed by two concepts:

- The public trust doctrine: Embedded in state law and constitutions, its essence is that government has a fundamental duty to maintain a regenerative natural environment for present and future generations. The state of Montana includes this provision in its constitution: "The state and each person shall maintain a clean and healthful environment in Montana for present and future generations." Decisions on large-scale projects like this one lie in the domain of the public trust. They involve public lands and mineral rights and public subsidies, and they affect future generations.
- The precautionary principle: "When an activity raises threats of harm to human health or the environment, precautionary measures should be taken even if some cause and effect relationships are not fully established scientifically" (Wingspread Statement, January 1998). Applying the precautionary principle to economic analysis means assigning value to human health and the environment; taking uncertainty into account; describing full costs and harms as well as benefits; describing the distribution of costs, benefits, and uncertainty; and examining alternatives.

Public benefits from CBM development

- At planned rates of extraction, methane would be produced in this region for about 20 years. The total amount would be the equivalent of about one year's supply of natural gas in the U.S.
- In Wyoming, USDA projects that CBM will turn a former state budget deficit into a $400 million surplus by the end of 2004, that CBM will bring 7000 new jobs to the state, and that the $1 billion investment by energy companies will translate to an overall net effect of $1.4 billion in all sectors of the Wyoming economy. An industry-funded analysis projects $4.2 billion in economic benefits for Montana.

Public costs of CBM development

1. Subsidies: $700 million to $1.7 billion over the next five years in federal tax breaks. Heavy subsidies for CBM development and technological advances in the past two decades have made CBM a viable resource, and it now represents about 7.5% of U.S. natural gas production. Nevertheless subsidies continue, largely in the following categories (see **Table 1**):
   - "Section 29" tax credit: This tax credit for alternative fuels was originally intended as a short-term measure to boost production from new sources. Subsidies are likely to be restored to CBM production. Legislation is in conference as of August 2004.
   - Percentage depletion: Independent oil and gas companies and royalty owners are allowed to

Table 1. Federal tax breaks available for the coalbed methane industry.

Tax Breaks 2005–2010	Total Cost
Section 29	$676 million – $1.57 billion
Percentage Depletion	$9.8 million – $38.1 million
Expensing development costs	$21.4 million – $42.8 million
Total tax breaks	$707 million – $1.65 billion

deduct 15% of their annual gross receipts from their taxable income. This means that the total amount deducted may eventually exceed the initial investment. It also tends to allow a larger deduction than the more standard method of cost depletion.

- Expensing development costs: Oil and gas companies are allowed to count most exploration and development costs as expenses, and deduct them all at once from their taxable income instead of depreciating them over time. This allows them to defer their tax payments and earn interest on the money.

2. Water costs:
   - Well remediation–$50 million: CBM development as proposed could pump up as much as 13 trillion gallons of groundwater. This removal of water will produce an estimated 600 foot drop in the coalbed water table in Montana and a 700 foot drop in Wyoming. Some 5000 water wells will be affected by the drop in the water table, with expense of $10,000 for each well that must be deepened or protected from contamination.
   - "Lost water": $2 billion to $10 billion over 20 years, i.e. $84 to $400 per person per year in Wyoming and Montana. These estimates are based on three conservative parameters: value of water per acre-foot ($258 to $900); number of gallons produced from planned CBM extraction (9 to 11 trilllion); percentage of water "lost," i.e. unsuitable or unavailable for reuse (25 to 50%).
   - Growing water demand: The arid West is still attracting migrants from throughout the U.S. One low-growth scenario estimates a 17% increase for the Powder River Basin and adjacent Tongue River Basin by 2025, with a high-growth scenario delivering a 36% increase.

3. Other costs: Plans are for up to 77,000 new wells in the region, more than five per square mile. Some 25,000 miles of unpaved roads and 47,000 miles of pipelines and power lines will transform thousands of acres of natural landscape into an industrial corridor. Costs to lifestyle, livelihood, and recreation, along with remediation expenses, will fall mostly to the public.

Summary of benefits, costs, risks, and their distribution (see **Tables 2** and **3**):

- The benefits of CBM development occur in the immediate and near future, while the costs spread over several generations.
- The benefits are highly concentrated, spilling over slightly to the public as a whole and to the public sector in the region, but still overwhelmingly concentrated with the oil and gas companies that would develop the resource.
- Significant public resources have been directed to this project, further enriching the small cadre of beneficiaries at the expense of the larger public.

Recommendations

1. Eliminate subsidies for CBM.
2. Institute environmental bonding to assure that those who use society's resources are held financially responsible for damages. The resource user would put into escrow an amount based on an estimate of the worst outcome of the proposed activity.
3. Develop cost-effective energy strategies. By 2008, wind energy will provide the equivalent of 3 billion cubic feet of natural gas per day, equivalent to 6% of total natural gas production. By 2020, natural gas use can be decreased by 31% from a business-as-usual scenario, with consumer savings of over $100 billion, by combining the shift toward renewable energy sources, which have lower long-term costs, with fuel-efficiency measures.

Full report by Joshua Skov and Nancy Myers is available at <http://www.sehn.org/pdf/cbm.pdf>. See full report for references.

Table 2. Summary of benefits to different groups from coalbed methane production.

Benefits of CBM development	Through 2017	2017 – 2060	2060 –
Oil/gas companies	Value of CBM extracted	None	None
Landowners in Powder River Basin with damage agreements	Compensation	None	None
Landowners in Powder River Basin without damage agreements	Compensation where damages can be established	None	None
Residents of MT and WY	Taxes on CBM, small gains in employment	None	None
Residents of United States	One year's supply of natural gas	None	None

Table 3. Costs to different groups from coalbed methane development.

Costs of CBM development	Through 2017	2017 – 2060	2060 –
Oil/gas companies	Expenses of CBM extraction and agreed damage compensation	None	None
Landowners in Powder River Basin with damage agreements	Disruption of current uses, contamination of wells	Lower water table, potential soil damage and contamination, decreased economic value of land.	Some continued impacts on water (even assuming 95% recharge) and soil; therefore, potential decreased economic value.
Landowners in Powder River Basin without damage agreements	Same as above, plus expense to establish damages for obtain compensation	Same as above	Same as above.
Residents of Montana and Wyoming	Loss of landscape, decreased recreation value in some areas, regional lower water supplies worth $2–10 billion	Regional lower water supplies, loss of landscape OR costs to remediate damaged lands	Continued remediation expense OR lowered value of damaged lands
Residents of United States	Substantial subsidies to oil/gas companies operating in region	Continued depreciation tax breaks; possible long-term burden of regionally degraded hydrology and remediation of damaged lands	Possible long-term burden of regionally degraded hydrology and remediation of damaged lands

Poster Sessions

Surface and ground water quality and quantity

*A system for collecting baseline and monitoring vegetation and related soils data–*Geneva W. Chong and Benjamin Chemel, U.S. Geological Survey; Paul Evangelista, Colorado State University; and Bruce West, U.S. Bureau of Land Management*

*Waters of Wyoming–*John Dewey, Sheridan, Wyoming*

Toxicity of coalbed natural gas product waters and receiving waters from the Powder River Basin, Wyoming–*M.B. Forbes, University of Wyoming; S.J. Clearwater, National Institute of Water and Atmospheric Research Ltd; B.A. Morris, University of Wyoming and U.S. Geological Survey; and J.S. Meyer, University of Wyoming*

**In situ* measurement of microbially-catalyzed nitrification and denitrification rates in stream sediments receiving coalbed methane discharge, Powder River Basin, Wyoming–*Steve H. Harris, Jr. and Richard L. Smith, U.S. Geological Survey*

*Quality of coalbed methane product water: Arsenic, boron, fluoride, and selenium–*I.H. MacBeth, K.J. Reddy, and Q.D. Skinner, University of Wyoming*

*Quality of coalbed methane discharge water interacting with semi-arid ephemeral stream channels–*M.J. Patz, K.J. Reddy, and Q.D. Skinner, University of Wyoming*

*Modeling of stream channel infiltration of CBM co-produced water and the effect on the shallow aquifer–*Aaron A. Payne, and Demian M. Saffer, University of Wyoming; and John R. Wheaton, Montana Bureau of Mines and Geology*

*Solubility of Ba, Cr, Mn, and Zn in coalbed methane (CBM) product water disposal ponds–*K.J. Reddy and Quentin Skinner, University of Wyoming*

Well completion, monitoring, and produced water treatment

*A conceptual design for assessing effects of CBM infiltration impoundments on groundwater quality–*Kevin D. Frederick, Wyoming Department of Environmental Quality, Water Quality Division*

*A unique method to remove selenium from CBNG produced water–*M.M. Patterson and K.J. Reddy, University of Wyoming*

A novel method to remove arsenic species from water–*A. Viswatej and K.J. Reddy, University of Wyoming*

Natural gas emission monitoring using a miniature fiber optic spectrometer–*R. Perry Walker, Photon-field Engineering*

Water use, soils, and wildlife

*Mud Springs walk-in pheasant habitat–*Kathy Hinkle, Devon Energy Production Company, L.P.*

Soil and vegetation impacts from land application of saline-sodic coalbed methane waters–*Lyle A. King, George F. Vance, and Girisha K. Ganjegunte, University of Wyoming*

*Chronic toxicity of $NaHCO_3$ to fathead minnows in water simulating the Tongue River, Montana, U.S.A.–*Brady Morris, University of Wyoming and U.S. Geological Survey; A.M. Farag, U.S. Geological Survey*

Information management, risk assessment, and legal issues

*Multi-scale, multi-disciplinary investigation of CBM development in the Powder River Basin of Wyoming: A Department of Interior Landscape Initiative Project–*C.A. Rice, T.T. Bartos, M.H. Brooks, G. Chong, and L. Clampitt, U.S. Geological Survey; P. Evangelista, Colorado State University; R. M. Flores, R.W. Healy, J. McBeth, R. Smith, and M. Sweat, U.S. Geological Survey*

*Adaptive management and planning models for cultural resources in oil and gas fields, New Mexico and Wyoming–*Mary Hopkins, Wyoming State Historic Preservation Office; Eric Ingbar, Gnomon, Inc.; Tim Seaman, New Mexico State Historic Preservation Office*

* Written paper was not available for this volume

Toxicity of coalbed natural gas product waters and receiving waters from the Powder River Basin, Wyoming

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Susan J. Clearwater–National Institute of Water and Atmospheric Research Ltd., New Zealand
Brady A. Morris–University of Wyoming, Laramie, Wyoming and U.S. Geological Survey, Jackson, Wyoming
Joseph S. Meyer–University of Wyoming, Laramie, Wyoming

We tested coalbed natural gas (CBNG) product waters and nearby stream waters from the Powder River Basin, Wyoming for acute and chronic toxicity to aquatic invertebrates. Acute toxicity tests were performed with an aquatic invertebrate (*Daphnia magna*; 48-h test) and a warm-water fish (fathead minnow–*Pimephales promelas*; 96-h test) exposed to full-strength sample water, using laboratory well water as the control. Several months later, we repeated the 48-h *D. magna* acute toxicity tests and also performed 192-h chronic toxicity tests with another aquatic invertebrate (*Ceriodaphnia dubia*) exposed to full-strength sample water and 50, 25, 12.5, and 6.25% dilutions, using moderately hard reconstituted water (Lewis and others, 1994) as the control. Additional details of the study design and results appear in Forbes (2003).

In the first set of *D. magna* and fathead minnow acute tests, CBNG-related waters did not cause significant mortality (**Table 1**). In the *C. dubia* chronic toxicity tests, mortality was significant in two CBNG product water samples (192-h LC50s = 90% and 39% of full-strength water) and one downstream water (192-h LC50 = 70% of full-strength water), where LC50 is the median lethal concentration of the sample water (**Table 2**). Additionally, reproduction decreased as concentration increased for all six of the CBNG product waters and for nine of the eleven stream waters tested (two composed entirely of CBNG discharge water, five downstream from CBNG development, and two whose proximity to CBNG activity was unknown; **Figure 1**).

Based on the limited set of samples we tested, approximately 1/10-strength CBNG product water does not appear to adversely affect survival or reproduction of *C. dubia*–a relatively sensitive aquatic invertebrate (e.g., see Mount and others, 1997).

Acknowledgements

Funding was provided by Beatrice Gallatin Beuf, The Tucker Foundation, and the Wyoming Department of Environmental Quality. Connie Boese, Sean Pfister, and Jennifer Zygmunt provided technical assistance with the toxicity tests and chemical analyses of CBNG-related waters.

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Table 1. Summary of acute toxicity results for *Daphnia magna* (48-h tests) and fathead minnows (FHM — 96-h tests) exposed to CBNG-related waters in Summer 2001.

Sample type	No. of waters causing significant mortality		Total tested
	D. magna	FHM	
CBNG product water	0	0	7
Entire flow of stream was CBNG product water	0	0	6
Stream, downstream from CBNG development	0	0	9
Stream, upstream from CBNG development	0	0	4
Unidentified source	0	0	4

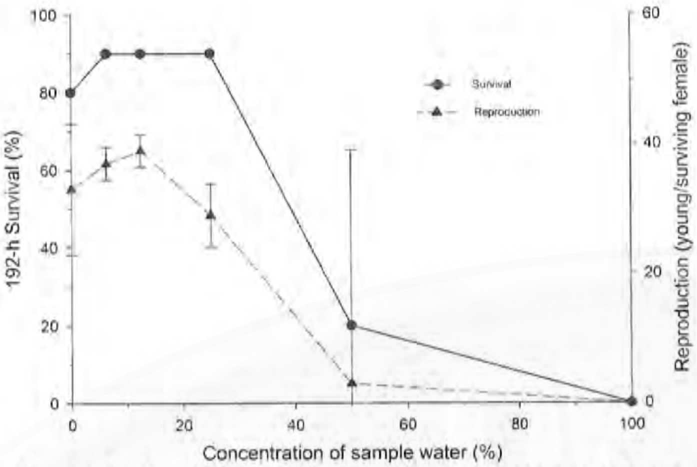

Figure 1. Survival and reproduction of *Ceriodaphnia dubia* in various dilutions of a CBNG product water from the Powder River Basin of Wyoming. The product water constituents were dominated by Na^+ (41 mM) and HCO_3^- (52 mM).

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Table 2. Summary of acute toxicity results for *Daphnia magna* (48-h tests) and *Ceriodaphnia dubia* (192-h tests) exposed to CBNG-related waters in Fall 2001.

Sample type	No. of waters causing significant mortality			Total tested
	D. magna 48-h	*C. dubia* 48-h	*C. dubia* 192-h	
CBNG product water	1	1	2	6
Entire flow of stream was CBNG product water	0	0	0	2
Stream, downstream from CBNG development	0	0	1	6
Stream, upstream from CBNG development	0	0	0	1
Unidentified source	0	0	0	2

Removal of arsenate and arsenite from contaminated waters using a novel technique

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Introduction

Arsenic (As) is recognized as a micronutrient essential to life (Krapf, 1983). The U.S. Environmental Protection Agency (EPA) proposed a new standard of 10 μg/L maximum contamination limits for the arsenic in drinking water. The sources of arsenic in natural waters are mainly the parent materials from which it is derived (Sandberg and Allen, 1975). Arsenic may accumulate in waters through use of arsenical pesticides, application of fertilizers, irrigation, dust from burning fossil fuels, and disposal of industrial and animal wastes. The common arsenic species found in natural waters are arsenate (+V) and arsenite (+III) (Nriagu, 1994). Studies have suggested that arsenite is more toxic than arsenate. Most conventional methods for arsenic removal have difficulties removing arsenite from the drinking water. Even though certain techniques are successful on large municipal supplies, they are not practical for residential application.

The groundwater pollution caused by arsenic in a number of Asian countries has led to a major environmental crisis. Some recent estimates indicate that more than 35 million people in West Bengal (India) and Bangladesh are potentially at risk from drinking arsenic-contaminated water (Rahman and others, 2001). Exploitation of groundwater wells for drinking water and for irrigation has resulted in increased mobility of arsenic (Smith and others, 2000).

It has been reported that long-term exposure to arsenic in excess of 0.05 mg/L in drinking water causes increased risks of cancer in the skin, lungs, bladder, and kidney. It also leads to other skin-related problems such hyperkeratosis and changes in pigmentation. Consumption of arsenic also leads to disturbance of the cardiovascular and nervous system functions and can eventually lead to death. These health effects, sometimes collectively referred to as arsenicosis, have been demonstrated in many studies (World Health Organization, 1999). Awareness about the pollution of drinking water with arsenic and the significance of the crisis rose significantly during the 1990s. It is now recognized that dealing with arsenic contamination in groundwater may be a problem of global dimensions.

Recent studies have shown that coalbed methane natural gas (CBNG) produced water contains small amounts of As. The objective of this study is to discuss effects of different interfering ions in removal of As from produced water using a product^{PM} (proprietary material) developed in the Water Quality Laboratory, Department of Renewable Resources, University of Wyoming.

Methods

Different concentrations of arsenate and arsenite were reacted with different amounts (0.1 to 0.5grams) of product^{PM} for 30 minutes. All experiments were conducted with 50 ml of each sample. After 30 minutes of reaction, samples were filtered with 0.45 micron filters and clear filtrates were analyzed for total arsenic using ICP Mass Spectrometry (analytical detection limit for As is 0.1 μg/L). In addition, experiments were conducted with the product^{PM} and different concentrations of arsenate and arsenite in the presence of different amounts of sulfate. Natural water samples from the Casper area and CBNG produced water from the Powder River Basin (PRB) were tested with product^{PM} to remove arsenic.

Results

Results from time dependent study with varying concentrations of arsenate and arsenite using 0.5 grams of the product^{PM} are shown in **Table 1**. These results suggest As adsorption by product[PM] is rapid. Results from influence of different amounts of product[PM] in removal of arsenate and arsenite from solutions are shown in **Table 2**. Even 0.1 grams of product[PM] was able to remove most of the arsenate and arsenite from standards within 30 minutes. Data from arsenate and arsenite adsorption reactions with 0.5 grams of product[PM] in the presence of competing ion sulfate are shown **Table 3**. These results suggest that sulfate showed very little or no interference in adsorption of As species by product[PM]. Results from the effect of 0.5 grams of product[PM] in removal of spiked arsenate and arsenite from natural waters are shown in **Table 4**. These data suggest the product[PM] removed most of the arsenate and arsenite from samples. In some cases, it removed As to below the detection limit of 0.1 µg/L. It is also evident that high concentrations of sulfate did not affect the adsorption of arsenate and arsenite by the product[PM]. The effect of 0.5 grams of product[PM] in removal of arsenic from CBNG produced water from different watersheds in the PRB is shown in **Table 5**. The proposed method also successfully removed arsenic associated with the CBNG produced water.

Conclusions

The product[PM] was never used before as an adsorbent to remove arsenic from the waters. It has a good affinity to adsorb both arsenate and arsenite from water. Results also suggested that product[PM] can remove As species in the presence of other ions such as sulfate. The additional advantage of this method is that it can work under natural water pH conditions. This technique is simple, economical, and efficient; it can be used to remove As from drinking water and/or contaminated water without adjusting the natural pH of the water.

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Table 1. Time dependent study with varying concentrations of arsenate and arsenite using 0.5 grams of the product[PM].

Time reacted (minutes)	1191 (µg/L) of arsenate	1030 (µg/L) of arsenite
5	BD	1.45
10	0.85	0.2
15	0.25	BD
20	0.05	0.75
25	BD	0.15
30	0.7	1.05

Table 2. Influence of different amounts of product[PM] in removal of arsenate and arsenite from solutions. Reaction time is 30minutes.

Product™ concentration (grams)	Concentrations remained after the reaction					
	288 (µg/L) of arsenate	265 (µg/L) of arsenite	539 (µg/L) of arsenate	516 (µg/L) of arsenite	1015 (µg/L) of arsenate	975 (µg/L) of arsenite
0.1	0.65	0.15	0.3	0.1	1.1	1.35
0.2	0.75	0.15	0.3	0.85	0.45	0.6
0.3	0.4	0.35	0.2	1.15	0.95	0.75
0.4	0.15	0.3	0.2	0.8	1.2	0.2
0.5	BD	BD	BD	BD	BD	BD

Table 3. Arsenate and arsenite adsorption reactions with 0.5 grams of product[PM] in the presence of competing ion sulfate. Reaction time is 30 minutes.

Arsenate/ Arsenite	Sulfate concentration after reaction (mg/L)	Sulfate concentration after reaction (mg/L)	Total arsenic concentration before reaction (μg/L)	Total arsenic concentration after reaction (μg/L)
Arsenate	1277.3	1268.6	430	1
	263.6	244.6	430	BD
	50.3	42.7	352	BD
Arsenite	1303	1293	555.8	4.1
	269	260	544.9	2.7
	64.2	57.9	610.4	BD

Table 4. Effect of 0.5 grams of product[PM] in removal of spiked arsenate and arsenite from natural waters. Reaction time is 30 minutes.

Arsenate/ Arsenite	Water Samples	Sulfate concentration before reaction (mg/L)	Total arsenic concentration before reaction (μg/L)	Total arsenic concentration after reaction (μg/L)
Arsenate	Oregon	404	120.1	0.5
	Six-mile	486	125.2	BD
	Casper	809	119	BD
	Bait's	377	117.8	BD
Arsenite	Oregon	401	121.1	1
	Six-mile	472	149.6	BD
	Casper	801	143.6	BD
	Bait's	379	142.5	BD

Table 5. Effect of 0.5 grams of product[PM] in removal of arsenic from CBNG produced water from different watersheds in the Powder River Basin. Reaction time is 30 minutes.

Water samples	Sulfate concentration before reaction (mg/L)	As concentration before reaction (μg/L)	As concentration after reaction (μg/L)
Bell Fourche River Basin	396	6.2	2.05
Powder River Basin	1.405	7.65	2.25
Cheyenne River Basin	4.395	4.15	1.8

Natural gas flare emission monitoring using a miniature fiber optic spectrometer

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Natural gas exploration and development has accelerated greatly over the past two years in the Jonah and Pinedale Anticline fields of Sublette County, Wyoming and the coalbed natural gas (CBNG) development in the Powder River Basin. Normal operations in at least two of these fields include well completion processes that involve burning or "flaring" of natural gas, which emits large volumes of air pollutants in the form of NO_xs, VOCs, and smoke (The Green Lane Environment, 2001). These emissions appear to be causing increased visible haze in the region but there is currently little effort underway to measure these emissions and verify their contribution to this haze. The author has undertaken an independent project to characterize emissions from flaring utilizing a miniature fiber optic spectrometer. The instrument is small, quite effective, and offers a new approach to monitoring pollutant gas emissions in oil and gas fields. Its effectiveness in this instance is illustrated by the fact that it has revealed hitherto unreported chemical elements in well completion flares.

Experimental methodology

This spectrometer is a laptop-computer-compatible Model USB2000 Plug-and-Play Fiber Optic unit that is manufactured and marketed by Ocean Optics, Inc. located in Dunedin, Florida. It has been configured for this application with a 2048-element CCD-array detector. Light is admitted through a 2-meter-long, UV optimized, 1000 um (micrometers) fiber, passed through a 25 um slit, and is dispersed via a fixed grating across the detector, which responds to wavelengths from 200 to 1100 nm (nanometers). The grating is optimized for UV-VIS with a groove density of 600 lines/mm (millimeter), blaze wavelength of 400 nm, and a "best efficiency" between 250 nm and 800 nm. The instrument must be cooled to suppress internal thermal noise and this is achieved with commercial "Blue Ice" packs sometimes combined with a thermoelectric cooler. **Figure 1** illustrates the configuration of the laptop computer, spectrometer, its two cooling pack options, and collector head; the latter is necessary to limit the optical field of view so peripheral light sources such as flood lights can be eliminated.

Figure 1. Computer, spectrometer, cooling options, and collector head.

The method of use that evolved is to carry the cooled spectrometer and laptop computer to locations where well flaring is underway at night. Nighttime observations offer the advantage of absence of solar masking of spectral well measurements because of the intense nature of the solar signal. Additionally, the measurement activity can be conducted in a manner that will not interfere with the activities of work crews. During

October and November of 2003, and again in March 2004 to the present, several spectral measurements have been collected. Measurements have been performed on completion flares and on flaring that takes place during drilling operations prior to completion.

Results

Spectra of well completion flares have a common appearance that is in itself not surprising. However, the particular shape of the spectrograms might seem odd in that the expected Planck black body radiation curve is absent and instead, there are two very sharp peaks in the visible portion of the spectrum. Specifically, an intense narrow peak occurs at 589 nm and a second less intense double peak occurs at 766 nm and 770 nm. Ultimately, the chemical origin of the 589 nm peak has been established as sodium and that of the double as potassium (Hodgman and others, 1961; Kelly and Decker, unknown; Volland, 2004; Kremens, 2001; and Vodacek and others, unknown). This seemed to pose a dilemma because natural gas does not normally contain these elements. Thus, in search of an explanation, attention has been focused on the well fracturing process.

When a well is completed, it is subjected to a process of fracturing or *fracing* which involves actually fracturing the down-hole rock strata so that gas may more freely flow toward the bore hole. This is accomplished by pumping fluids referred to as borate gels, consisting of complex polymer chemicals, down the hole. This initial fluid or base gel is composed of a liquid guar concentrate prepared in diesel, which is added to tanks of water that contain additives and the chemical compound KCl. Completed fluid is formed by adding cross linking agents to the base gel as well as substances called "breakers," breaker activators, stabilizers, and non-emulsifiers. Two chemical compounds used as breakers are *sodium persulfate* ($Na_2S_2O_8$) and *sodium tetraborate decahydrate* ($Na_2B_4O_7$-$(H_2O)_{10}$ (Halliburton Corp., unknown, and Environmental Protection Agency, 2004). Ultimately, the gel is returned to a fluid state by the breaker and the natural high pressure of the gas flushes the fluid back to the surface and into the flame pit where the flare is underway. It is therefore highly likely that the gas stream being routed to the flame pit carries substantial amounts of the chemicals $Na_2S_2O_8$ and KCl in addition to natural sodium dissolved in ground water which are all ionized by the energy of combustion and in their excited state produce the observed spectral peaks (Kremens, 2001).

Figure 2 is a typical completion flare spectrum and **Figure 3** is the photograph of that flare. The peak at 589 nm corresponds exactly with the established location of the strong sodium emission line, often referred to as the "D" line (Keesee, 2004 and Volland, 2004). The double peak at 766 nm and 770 nm corresponds exactly with the established location of the doublet for potassium (Hodgman and others, 1961 and Kelly and Decker, unknown). The intensity of these peaks is sufficient to overpower the Planck black body radiation curve that should be characteristic of the flare's apparent surface brightness (Kremens, 2001). A variation on this spectrum is seen in **Figure 4** with its accompanying photo in **Figure 5**. Here, for reasons not clear, the potassium peak is more intense than the sodium peak. Subsequently, another emission peak has been detected at 670 nm. This wavelength closely matches the brightest emission band of the element lithium (Hodgman and others, 1961; Volland, 2004; and Field, 2001). The lithium peak is easily missed in most of the well spectra collected because of the over-powering intensity of the sodium and potassium components but there are a few in which the peak definitely appears, thus suggesting varying levels of concentration of that element in the gas flow of the flare. This spectrum is seen in **Figure 6** with its accompanying photo in **Figure 7**. In most other completion flare observations, associated spectra were similar in shape to that in **Figure 2**. **Figure 8a-d** shows an eleven minute

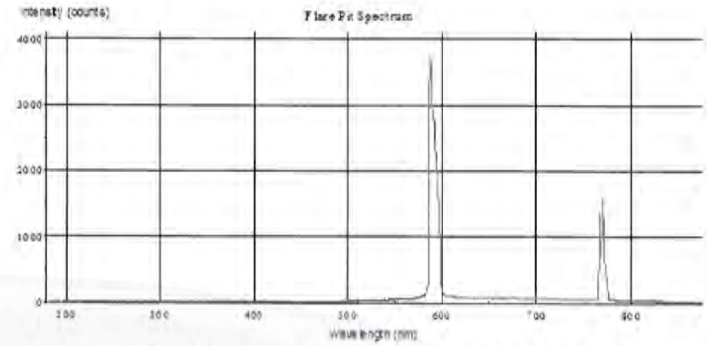

Figure 2. Typical completion flare spectrogram.

Figure 3. Photograph of flare in Figure 2.

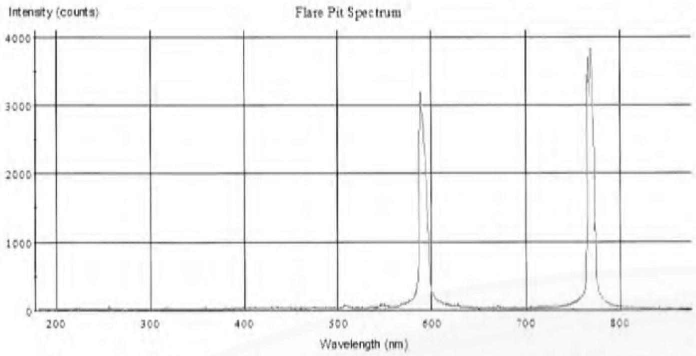

Figure 4. Example of sodium/potassium intensity reversal.

Figure 5. Photograph of source of Figure 4 spectrogram.

evolution in a flare's spectral signature resulting from surges of fracing fluid coming to the surface.

Conclusions

The detected presence of sodium, potassium, and lithium optical signatures in well completion gas flares should indicate a cause for concern among health officials regarding possible air quality impacts upon regional human and wildlife populations. Although the gas industry is moving toward flareless well completion technology, there are operators that continue to employ flare completion for reasons of economics.

Regulatory agencies at both the state and federal level should take notice of this development and initiate a comprehensive investigation of potential additional health hazards posed by these detected alkali elements in the plume emissions of flares. It should be a matter of importance to ascertain what compound forms these elements assume and their concentrations in the regional

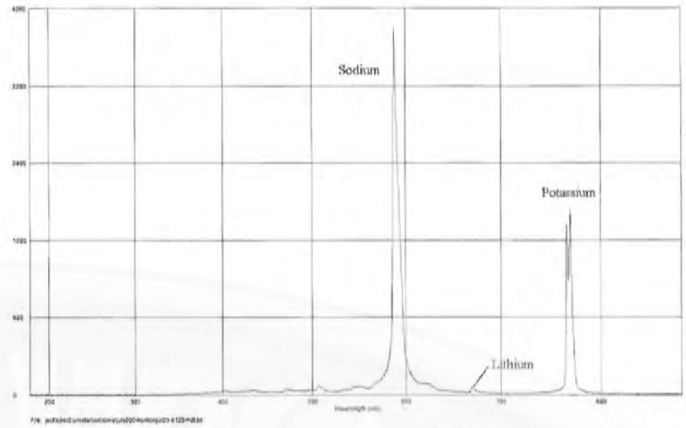

Figure 6. Smoke plume during initial flare period.

Figure 7. Spectrogram of flare in Fig. E showing Na, K, and Li peaks.

air mass. This will be necessary for regulators to make informed decisions. In the mean time, it may be prudent for regulators to place severe restrictions upon operators limiting the execution of well completion flaring to very brief episodes.

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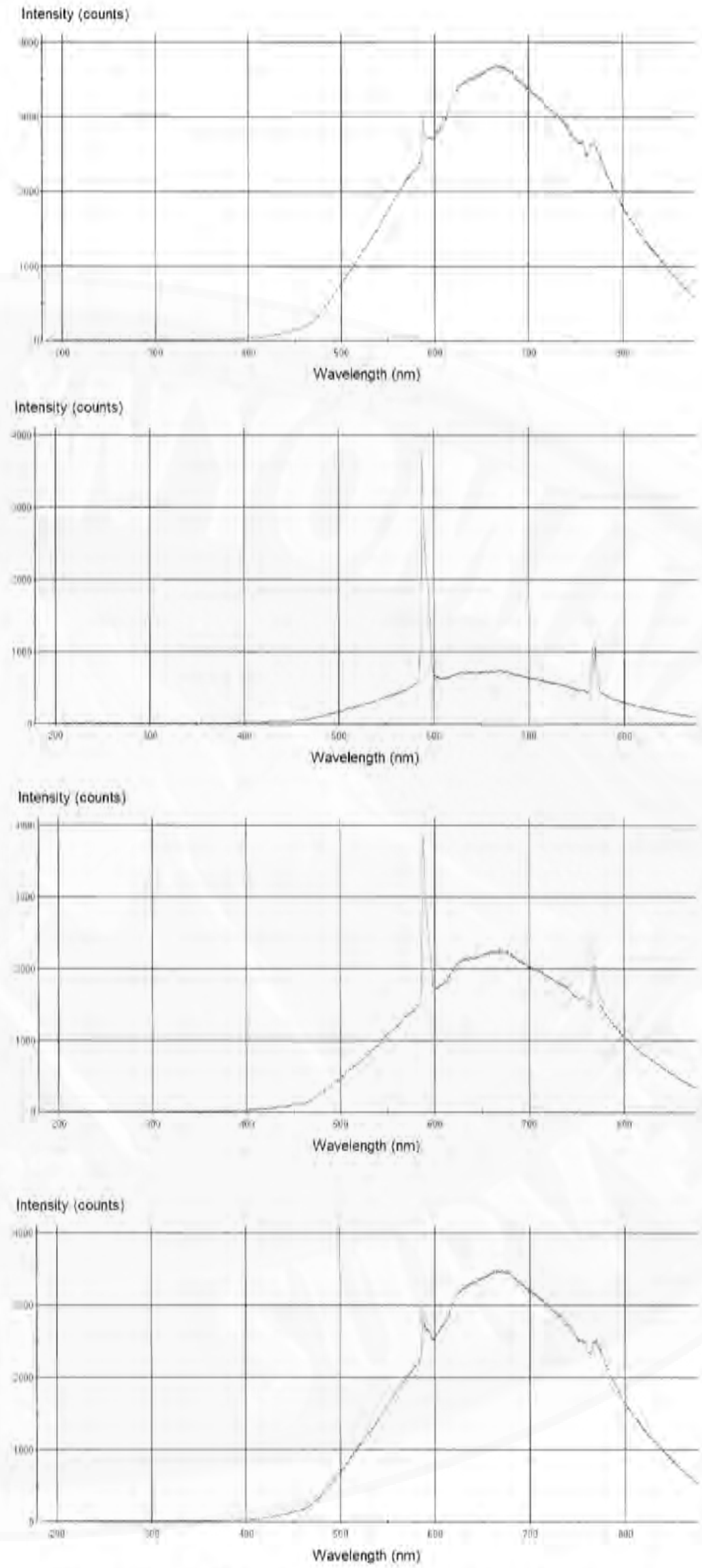

Figure 8a-d. Time lapse variations in alkali metal signatures indicating fracing fluid surges to the surface during an eleven minute period.

Soil and vegetation impacts from land application of saline-sodic coalbed natural gas co-produced waters

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Abstract

Impacts from land application of saline-sodic, coalbed natural gas (CBNG) co-product water on soil chemical and physical properties and on several vegetation characteristics are being investigated in northern Wyoming's Powder River Basin (PRB). Data from the 2003 and early spring 2004 field seasons are summarized from six study sites representing between one and four years of CBNG water application with center-pivot and side-roll irrigation methods. CBNG water applied to these sites had electrical conductivity (EC) values ranging from 1.8 to 4.0 dS m^{-1} and sodium adsorption ratio (SAR) values ranging from 15 to 38. Comparisons between treated plots (irrigated with CBNG water) and non-treated control plots on each site indicated consistently slower infiltration rates (surface) and hydraulic conductivity rates (depths to 120 cm) with treatment. Average soil EC and SAR values were significantly ($p<0.05$) increased at depths from 0 to 60 cm on treated compared to control sites. No consistent soil pH trends were apparent. Sites with two to three seasons of CBNG water application supported increased native perennial grass biomass production. However, total biomass production responses were mixed, and the aerial cover and diversity of non-grass species decreased with CBNG water application relative to control sites. Two years of CBNG water applications increased mycorrhizae infections of three native perennial grass species relative to control sites.

Introduction

Active CBNG exploration and production is occurring in the PRB with over 20,000 wells permitted or drilled and an estimated 50,000 to 100,000 future wells (Wyoming Oil and Gas Conservation Commission, 2003). CBNG production requires extensive coal seam dewatering and direct land application has been identified as one water management option. Large volumes of CBNG water are currently being applied to agricultural and non-cultivated lands using various irrigation systems such as center-pivot. Successful land application of saline-sodic CBNG water requires management strategies that encourage infiltration and leaching throughout the soil profile to limit salt accumulation and reduce impacts of high EC and SAR waters on soil and vegetation (King and others, 2004). Once land applications cease, successful reclamation will require understanding impacts to chemical, physical, and biological components to address issues that include erosion as well as clay and organic matter dispersion with subsequent surface crusting and reduced infiltration rates.

Methods and materials

The PRB is located in north-central Wyoming and south-central Montana. It is bounded on the west by the Big Horn Mountains, on the east by the Black Hills, and on the south by the Casper arch. Rolling uplands and hills are characteristic with rough, eroded broken terrain in the northern portions (U.S. Bureau of Land Management, 2003). Soils from six treated (irrigated) sites and five representative, non-treated control sites were sampled three times during the 2003 field season (early, mid, and late season). Vegetation data (production, aerial cover, diversity, and mycorrhizae infectivity of select plant species) were also collected.

Summary of results

Land application of saline-sodic CBNG water (for one to three years) has significantly elevated soil EC and SAR in 0 to 60 cm depths of treated sites. Average elevated levels do not exceed Wyoming Department of Environmental Quality/Land Quality Division suitability standards for vegetation growth (EC<8.0 dS/m^{-1}, SAR<12); however, these levels are exceeded on some sites.

Infiltration and hydraulic conductivity rates decreased with CBNG water application.

Saline-sodic CBNG water application increased native perennial grass production, cover, and mycorrhizal infection of selected species. Production, cover, and diversity of non-grass species, however, decreased with CBM water application.

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Impacts of CBNG co-produced water on soil physical and chemical properties

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Abstract

Impacts of land application of coalbed natural gas (CBNG) waters on soil physical and chemical properties were evaluated in sites from northwestern Powder River Basin (PRB), Wyoming. Results of CBNG water analyses indicated that electrical conductivity (EC) and sodium adsorption ratio (SAR) values were greater than the recommended values for irrigation use (0.75 dS m-1 and <10 SAR). Soil physical properties suggested that bulk density values for subsoil horizons were greater than surface layers; infiltration rates in control plots were consistently greater than irrigated plots [statistically significant ($p < 0.05$) for site 5], and hydraulic conductivities for irrigated fields were lower than control sites throughout the profile. The EC values for irrigated sites were significantly greater than control plots in the upper 60 cm. In addition, SAR values were significantly greater in irrigated sites compared to control plots within the upper 60 cm of most sites. Thus, irrigation with poor quality CBNG water had significant impacts on soil chemical and physical properties. It has been estimated that over the next 15 years CBNG water production in the PRB will exceed 366,000 ha-m. The results of this study will be useful to understand the potential changes in soil properties due to land application of CBNG water and to develop possible mitigating criteria for preserving impacted PRB ecosystems.

Introduction

Coalbed natural gas is considered an important source of natural gas and its production is a fast-growing industry in the PRB of Wyoming and Montana. Current estimates suggest there are about 15,000 CBNG wells permitted in the PRB with another 40,000 wells predicted by 2012 (U.S. Bureau of Land Management, 2003). Natural gas production is accomplished by pumping water from coal seams to reduce hydraulic pressure and facilitate gas migration. Due to the quality of CBNG water from some wells (SARs of 5 to 70 and EC of 0.4 to 3.9 dS/m) (Rice and others, 2002), extraction of large volumes (the cumulative CBNG-water production during the period 2002-2017 is estimated to be 366,000 ha-m) of these waters presents a great concern (U.S. Bureau of Land Management, 2003). Land disposal is becoming a popular option for managing CBNG water with many gas companies. Soils in the PRB are dominated by smectitic clays (U.S. Bureau of Land Management, 2003) and 40% of the PRB is characterized by poor drainage. Application of varying quality water derived from CBNG wells can have impacts on soil properties (Ganjegunte and others, 2004). This study evaluated changes in soil physical and chemical properties in six sites in Wyoming that have received CBNG water application for up to 3 years.

Study objectives

1. Characterize quality of CBNG water in the study area.
2. Evaluate impacts on physical properties–bulk density, infiltration rates, and hydraulic conductivity.
3. Assess effects of CBNG water application on soil chemistry–pH, EC, and SAR.

Materials and methods

Management history records were used to select study sites in the PRB region.

1. Water samples were collected for evaluating CBNG water quality–pH, EC, and SAR.

2. Soil samples from irrigated fields that have received CBNG water up to 3 years and control sites were collected from six different depths: 0-5, 5-15, 15-30, 30-60, 60-90, and 90-120 cm.
3. Soil physical properties determined included: bulk densities at 0-5, 5-15, and 15-30 cm; infiltration rates; and hydraulic conductivities at 15, 30, 60, and 90 cm.
4. Soil chemical properties determined included: pH, EC, and SAR of irrigation waters and soil saturation paste extracts.

Results

1. Water chemistry data indicated that CBNG waters being used for land application are not suitable for direct irrigation.
2. Bulk densities of subsoils from irrigated sites are greater than control sites–might be due to clay dispersion.
3. Infiltration rates were greater in control sites than irrigated sites except for site 2, which has received just one irrigation.
4. Hydraulic conductivities in irrigated sites were lower than control sites throughout the soil profile.
5. The EC of soils from CBNG water irrigated sites were greater than control sites except for site 2 that has received just one round of irrigation. Soil EC in irrigated sites decreased with depth up to 30 cm.
6. The SAR values of CBNG water irrigated sites are greater than control sites. This is more pronounced in site 1 that received CBNG water irrigation for more than 3 years.

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Use of plants and fish waste amendments for bioremediation of coalbed natural gas waters

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Introduction

Coalbed natural gas (CBNG) is recovered by pumping water from coal seams to reduce hydrostatic pressure that retains the methane. A primary concern with CBNG development in the Powder River Basin (PRB) Wyoming is what to do with this water. Some of the water is used by farmers and ranchers for livestock watering, irrigation, and other purposes. CBNG co-produced water is often applied to arid land surfaces in hopes that it will leach below the rooting zone. Two important factors that affect leaching are acceptable water quality and soils with adequate drainage potential. Water with high salts and sodium adsorption ratios (SAR) discharged on fine-textured soils (i.e., clay loams) has the effect of sealing the soil surface, causing soil dispersion, preventing leaching, and causing a build-up of harmful salts. The result is an inability of the land to support desirable vegetation due to land degradation.

Halophytes are plants that thrive in saline environments; some accumulate salts and incorporate them into their plant tissue. Fourwing saltbush, accumulates salts, accepts heavy watering, grows quite rapidly, has a protein level of 14-18%, is used for forage by cattle, and may provide cattle with supplemental salts when grown in CBNG water. A variety of barley, Busch Ag malting barley hybrid B1202, has been developed for growth in arid, higher altitude areas of Wyoming, Montana, and Colorado; the grain tolerates salinity and has commercial value. Another plant that is common to rangelands, crested wheatgrass, was also considered for this study.

Manures from fish have been applied to terrestrial and aquatic plants worldwide with considerable and continuing success. Both N and P contents have been quantified, and land applications of these manures are utilized whenever possible. In this experiment, our interest was to provide a system to improve discharge water quality by reducing the SAR and to produce an economically valuable crop. The growth of plants utilizing CBNG discharge water was examined in the presence and absence of nutrients derived from fertilizer and fish farm effluents. Objects of our study were to determine the effect of plant growth with different water treatments and included: leachate EC, Na and SAR; plant biomass and Na uptake; and soil saturation paste extract pH, EC, Na, and SAR characteristics.

Study parameters

Greenhouse study utilized three plants (crested wheatgrass, malting barley, and fourwing saltbush) and four water-soil treatments (control, CBM water, CBM + fertilizers, and CBM + fish water). Control waters used to irrigate pots to field capacity were from a mountain spring near Story, Wyoming, that has been utilized for irrigation. CBM water was collected from a CBM well. Inorganic N and P fertilizers were added at fertility levels; surface soil applications of N and P were at rates of 94 and 56 pounds per acre (105 and 63 kg/ha), respectively. CBM + fish water was a mixture of 1:25 (fish manure:CBM water) ratio. A 3 x 4 factorial randomized block design (plant biomass, Na uptake, soil chemistry) with four replications ($n = 48$) was used; for soil leachates only three replicates were evaluated ($n = 36$). A two-way analysis of variance (ANOVA) was conducted on plant and soil data to evaluate significant differences among treatment means. Effects due to water quality, plant types, and interactions between plant and water types were evaluated using LSD at the $p < 0.05$ level.

Summary and conclusion

Approximately 11 to 15 inches (28 to 38 cm) of water was applied to the pots. Many crops require approximately 20 to 40 inches (50 to 100 cm) depending on soil types and plant communities. Total N added to the soil was: < 1, 2-4, 15-24, and 110 pounds per acre (1.1, 2.2-4.5, 17-27, 123 kg/ha) for the control, CBNG water, CBNG + fish water, and CBNG + fertilizer treatments, respectively. Plant growth to N was not consistent. Soil leachate pH, Ca, and Mg were not significantly different among plant types and water treatments; however, EC, Na, and SAR were. If EC of 4 or greater is considered a problem, none of the treatments would be a concern. There was higher leachate Na in the wheatgrass and barley plant treatments when watered with the CBNG + fish water.

SAR for the three CBNG water treatments, irrespective of plant type, ranged between 4 and 9, which is acceptable if there is sufficient salinity associated with the solution. Fertilizer and fish manure enhanced plant growth, with fish manure as good as fertilization. Wheatgrass and barley responded to nutrient additions, whereas saltbush displayed a positive response to all three CBNG water treatments. Plant Na was greatest in barley grown using the CBNG + fertilizer treatment, which exceeded Na uptake of the other plants. Na accumulated in the saltbush plants when irrigating with the three CBNG water treatments and would be expected to be amenable for irrigation using CBNG waters.

Soil chemical (e.g., pH, EC, Na, and SAR) changes varied more with type of plant rather than quality of water. CBNG + fish water treatments resulted in the highest soil EC values for all three plants. Average EC values remained under 2.0 dS/m, which is suitable for plant growth. Both wheatgrass and barley treatments had higher soil Na concentrations than saltbush, which could be due to saltbush's ability to accumulate more Na in its biomass. Soil SARs were higher than leachate SARs, reflecting increased soil Na adsorption. Leaching Na and the other salts associated with CBNG waters could be enhanced by increasing the overall leaching potential.

Indiscriminate CBNG water discharge causes soil salinization and sodification that will impact plant growth. Improved soil and water environmental practices provide complementary, alternative, sustainable tools for improved and acceptable stewardship. Investigating the tolerances of native and agricultural plant species to the application of saline-sodic CBNG water will provide information on how to manage for enhanced reclamation potential. Additional research should evaluate various plants, true field conditions, tilling and irrigation practices, and soil leaching. Information is needed for accurate remediation, regulation, and permitting of the CBNG water land application practices.

Application of remote sensing and ground truth techniques in determining the effects of coal bed natural gas (CBNG) discharge waters

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The coalbed natural gas (CBNG) play in the Powder River Basin of northeastern Wyoming and southeastern Montana is currently the most active in the U.S. Water generated during gas production presents environmental concerns because the water typically contains high levels of salt and is generally discharged at the surface, possibly resulting in the alteration of soil properties and changes to vegetation biomass. This study utilizes Landsat Enhanced Thematic Mapper (ETM) data and field observations for change analysis in a region of CBNG production along Spotted Horse Creek in northeastern Wyoming. Hypotheses examined in this study are: 1) soil moisture and vegetation biomass increase with the addition of CBNG waters; and 2) CBNG waters affect soil chemistry.

The study site selected is a portion of T56N R76W and T56N R75W (**Figure 1**) where some CBNG waters have been used for irrigation/re-injection and others surface discharged. The water produced by the western-most wells in T56N R76W (Inkline Project) is re-injected into the Fox Hills Sandstone (approximately 6000 feet deep) in the winter months and used for irrigation the rest of the year. This irrigation water is pumped to a center-pivot sprayer approximately 300 feet in length that irrigates 47 acres of brome grass for a local ranch. The relatively expensive re-injection procedure involves filtering the water to remove sediment and then sterilizing it by chlorination before pumping it down the injection well. Water produced by the eastern-most wells in T56N R76W (Kline Draw Project) and all water produced from CBNG wells in T56N R75W (LS Draw Project) is surface discharged at various points into small draws or holding ponds in the vicinity of Spotted Horse Creek. Wells in T56N R76W tap the Canyon and Cook coals of the Wyodak-Anderson coal zone, while the wells in T56N R75W tap the Canyon, Cook, and Wall coals.

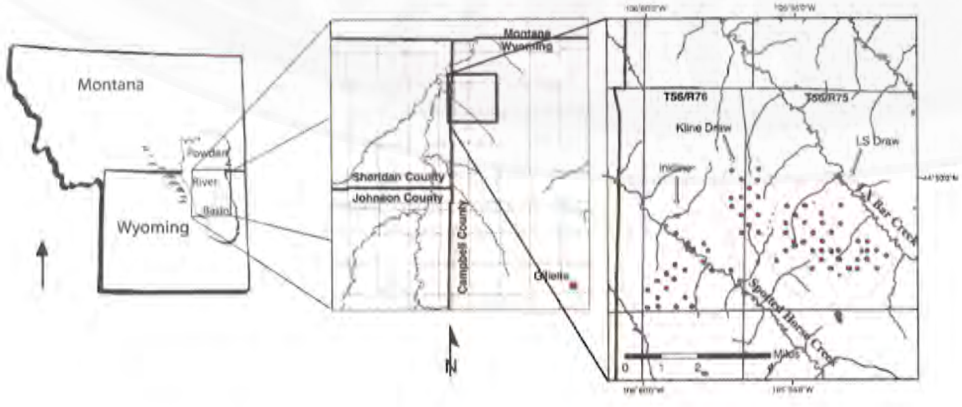

Figure 1. Index map showing the location of the study region, project areas, and wells along Spotted Horse Creek.

Little CBNG production occurred prior to 1999, but many producing wells were in place by the summer of 2002. During these three years, the number of producing CBNG wells in this study area increased from 68 to 138 (Wyoming Oil and Gas Conservation Commission Website, http://wogcc.state.wy.us/). The associated increase in water production (1100 %) over a relatively short period of time and the various methods employed in handling excess water make this an excellent site for applying remote sensing as a tool for monitoring surface effects over a relatively large area. Furthermore, comparison between the different water disposal practices (irrigation/re-injection and surface discharge) allows comparison of techniques that might be used to mitigate long-term effects of CBNG-water production.

This study utilizes a series Landsat ETM images for change detection analysis for the study area. Three Landsat ETM scenes were acquired to represent surface conditions during the summers of 1999, 2001, and 2002.

Pre-processing consisted of image registration, radiometric correction using dark-object subtraction, image scaling, and extracting a sub-image for the area of the study and its immediate surroundings. Each image was then classified according to soil moisture and vegetation biomass using the Tasseled Cap transform (Kauth and Thomas, 1976; Kauth and Crist, 1986). Change maps were computed for soil moisture and vegetation by subtracting the moisture and vegetation indices from the transform. The 1999 soil moisture and greenness values were compared to those computed for the 2001 imagery (a two-year span). The 2001 indices were compared to those computed for the 2002 imagery (a one-year span). Image maps computed in this fashion formed the base data set for evaluating changes at the surface (**Figures 2, 3,** and 4). Changes in surface condition were field checked, and representative soil and water samples were collected and analyzed for reference in interpreting the changes.

Results indicate the surface application of CBNG waters at the Spotted Horse Creek study site has initially increased soil moisture and vegetation in areas of CBNG activity. In the short term, the application of CBNG waters has increased vegetation biomass and helped mitigate some of the effects of prolonged draught. However, the CBNG waters are very high in salinity and sodicity, so the soil chemistry is gradually affected. Salinity, pH, and sodicity levels have changed to the point that the soils are becoming sodic. Presently, these levels are below the thresholds for most of the forage vegetation in the region but they are expected to increase with the continued discharge of CBNG waters. A linear projection of the observed changes produces an estimate for salinity and sodicity indicates that it will take approximately 11 years to reach the salinity threshold for crested wheatgrass (common to the region). Other species may be negatively affected at some earlier date and corresponding changes in plant community will certainly ensue.

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Kauth, R.J. and Thomas, G.S., 1976, The Tasseled Cap–a graphic description of the spectral-temporal development of agricultural crops as seen by Landsat, Proceedings of the Symposium on Machine Processing of Remotely Sensed Data, Purdue University, West Lafayette, Indiana, p. 4B41-4B51.

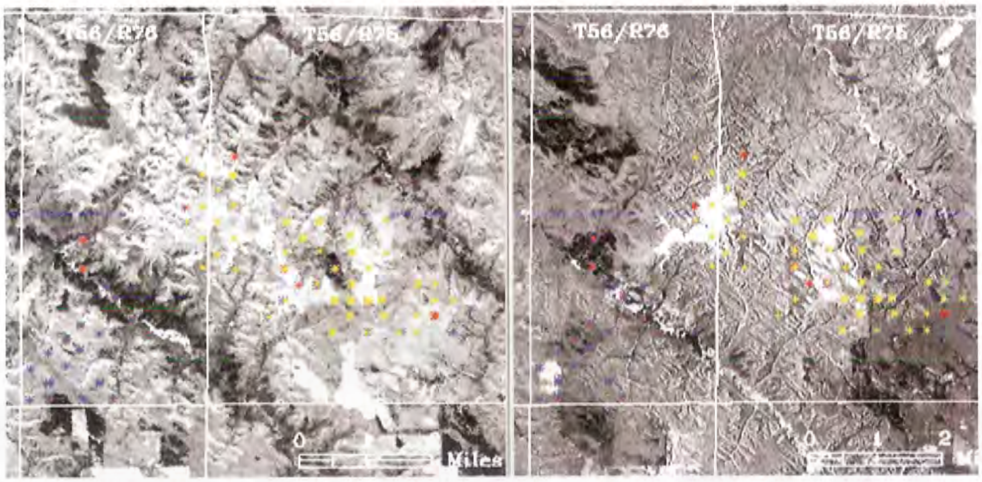

Figure 2. Vegetation change maps computed from the "greenness" component of the Tasseled Cap transform. Bright areas indicate increase in vegetation while dark areas indicate diminished vegetation vigor. Asterisks show the location of CBNG wells, with yellow indicating start dates in 1999, blue in 2000, and red in 2001. Many changes in vegetation are apparent, but most have to do with changing farming practices or draught. For example, the relatively large areas showing increase of vegetation in the Kline and LS Draw regions are fields recently affected by cultivation. The effects of CBNG discharge waters are largely confined to the narrow draws and drainages. A notable exception is the bright area near the lower left corner of the 2001-2002 change map. This area shows increase in vegetation due to sprinkler irrigation with CBNG water.

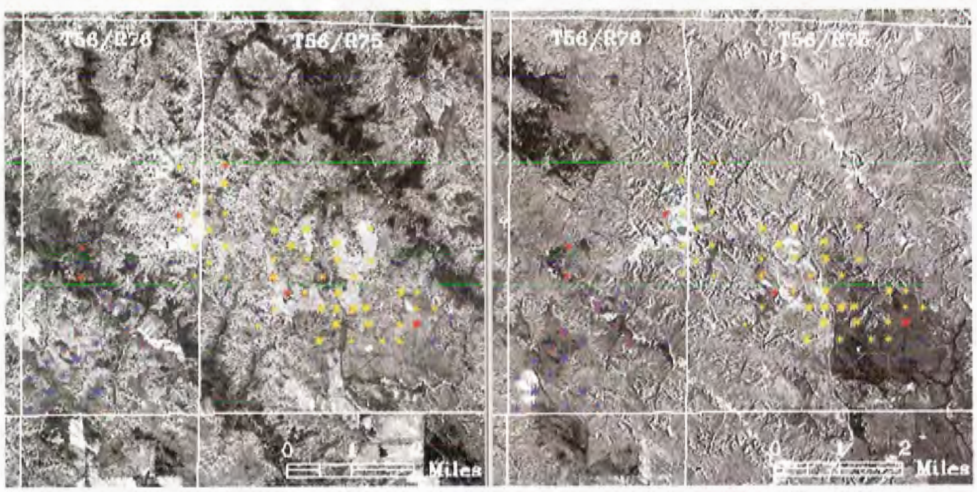

Figure 3. Soil moisture change maps computed using the soil moisture component of the Tasseled Cap transform. Bright areas indicate an increase in soil moisture. Asterisks show the location of CBNG wells, with yellow indicating start dates in 1999, blue in 2000, and red in 2001. The apparent increase to soil moisture in the Kline and LS Draw project areas is due to cultivation rather than CBNG discharge waters. The effects of CBNG discharge waters are mostly confined to the small draws and drainages. One notable exception is the very bright area near the southeast corner of the 2001-2002 change map, where the CBNG waters have been used to irrigate a field via a center-pivot sprinkler system. Strong similarities between soil moisture and vegetation change maps reflect the expected correlation between soil moisture and vegetation in this semi-arid region.

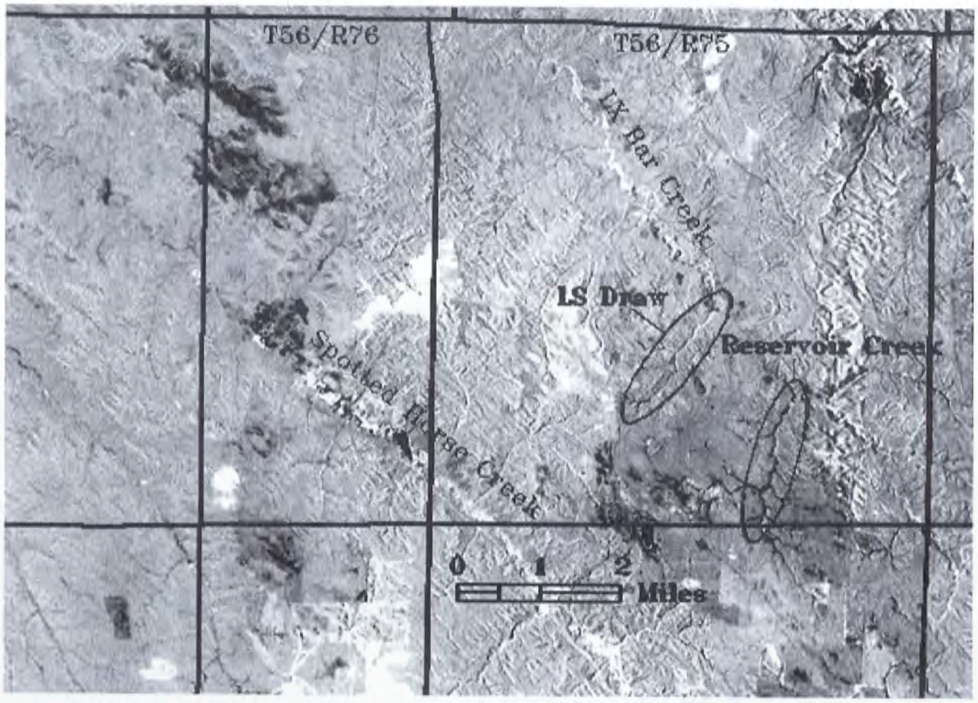

Figure 4. LS Draw and Reservoir Creek locations are indicated by ovals on the 2001-2002 vegetation change map. The change maps indicate increases in vegetation in the LS draw area (CBNG-affected) relative to the Reservoir Creek area (unaffected by CBNG water discharge). Both drainages are similar in size and flow northeast into LX Bar Creek. The image is the 2001-2002 change map produced by digitally combining "greenness" transforms from Landsat images for 2001 and 2002.

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