LAND APPLICATION OF COALBED METHANE WATERS: WATER MANAGEMENT STRATEGIES AND IMPACTS[1]

L.A. King, G.F. Vance, G.K. Ganjegunte and B. Carroll[2]

Abstract: Saline/sodic waters derived from wells associated with coalbed methane (CBM) gas production are being applied to rangelands and to lands used for production agriculture within the Powder River Basin (PRB) of Wyoming and Montana. Our study areas represent variable vegetation types, soil textures, treatment strategies and water application methods on sites impacted by up to 3 years of land application of saline/sodic CBM water. Vegetation parameters evaluated were forage quality, above ground biomass production, aerial cover, species diversity and infectivity of arbuscular mycorrhizae (AM) fungi. Soil data from six depth intervals to 120 cm were collected early summer, mid/late summer and fall during the 2003 water application season. Samples were analyzed for texture, bulk density, pH, electrical conductivity (EC), and sodium adsorption ratio (SAR). Infiltration and hydraulic conductivity rates were also measured. Waters from CBM gas wells in the PRB vary in quantity and quality, with average flows of around 30 liters per minute, salinity levels of about 2 dS/m and SAR's ranging from low (e.g., 5) to extremely high (e.g., 70) levels. Variable water application methods including center-pivot and side-roll irrigation and "mister" evaporation systems are utilized for land application. Common CBM water treatment strategies include: 1) varying application rates; 2) chemically treating water to adjust for SAR, salinity, pH and bicarbonate levels; and 3) chemically treating soil surfaces to minimize sodicity and salinity conditions. Potential advantages and disadvantages of various management strategies are discussed based on soil and vegetation data analyses. With about 20,000 CBM gas wells currently permitted or drilled in the PRB and estimates of at least 50,000 future new wells, proper CBM product water utilization is warranted.

Additional Key Words: saline-sodic water, infiltration rates, Powder River Basin, sodium adsorption ratio.

---

[1]Paper was presented at the 2004 National Meeting of the American Society of Mining and Reclamation and the 25th West Virginia Surface Mine Drainage Task Force, April 28-24, 2004. Published by ASMR, 3134 Montavesta Rd., Lexington, KY 40502.

[2] Lyle A. King, Ph.D. Student lyleking@uwyo.edu; George F. Vance, Professor; Girisha K. Ganjegunte, Post-Doctoral Research Associate, Soil Science Division, Department of Renewable Resources, University of Wyoming, Laramie, WY 82071. Brandy Carroll, Undergraduate Student, Department of Soil and Crop Science, Colorado State University, Fort Collins, Colorado 80521.

Proceedings America Society of Mining and Reclamation, 2004 pp 1056-1075
DOI: 10.21000/JASMR04011056

https://doi.org/10.21000/JASMR04011056

Introduction

Fossil fuel combustion remains the mainstay of U.S. energy production, and natural gas plays a critical role in supplying this need. Annual natural gas consumption rates in the U.S are about 623 billion m^3 (Bm^3) with the resource now heating more than 50 percent of U.S. homes and fueling 95 percent of new power plants (USDE-OFE, 2002). The U.S. has extensive reserves of coalbed methane (CBM), which is natural gas trapped in coal seams. These CBM reserves have become an important new energy source, supplementing traditional natural gas production, and now accounting for nearly 10 percent of the Nation's total natural gas production (Pinkser, 2002). The Powder River Basin (PRB) of Wyoming and Montana is an important CBM production area, currently accounting for about 20 percent of the nearly 113 million m^3 (Mm^3) of CBM produced per day in the U.S. (Fig. 1). Indeed within the next 10 years, it is estimated that as much as 75 percent of the growth in CBM production will occur within the PRB, which has an estimated 1.1 trillion m^3 (Tm^3) of technically-recoverable reserves (USDE-OFE, 2002). To meet these demands, over 20,000 CBM wells have been permitted or drilled within the PRB and extensive exploration and development activities continue with estimates of the eventual total number of new wells ranging between 50,000 and 100,000 (WY-OGCC, 2003).

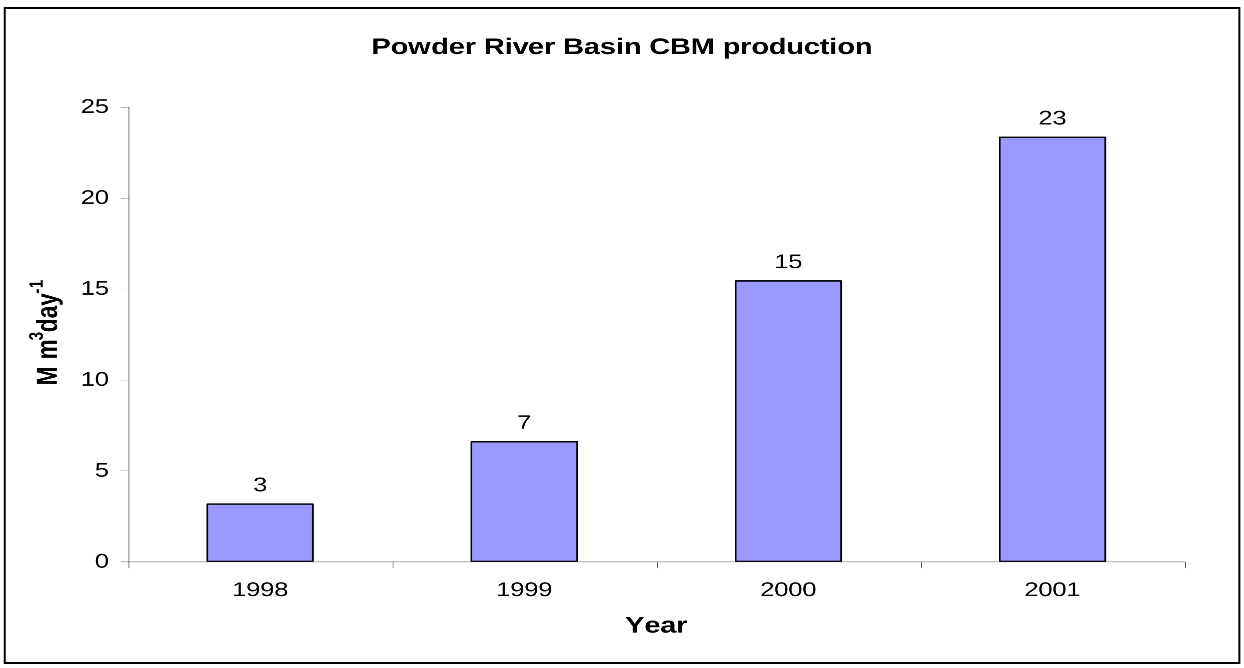

Figure 1. Powder River Basin is the site of the nation's fastest growing domestic natural gas play, the development of coalbed methane (CBM) (USDE-OFE, 2002).

Production of CBM requires extensive coal seam dewatering to reduce hydrostatic pressure within the coal, which allows methane gas to flow to the well head. Water production rates vary but discharge flows between 1 and 100 liters per minute (lpm) are normal and can continue from a single CBM well for up to 20 years depending on local conditions (Wheaton and Metesh, 2002). Coalbed methane water production in the PRB has been projected to peak in 2006 at nearly 47,000 hectare-meters (ha-m) per year (BLM, 2003).

CBM production water in the PRB is dominated by sodium (Na) and bicarbonate (HCO_3^-) ions, with pH ranging from 6.8 to 8.0, electrical conductivity (EC) from 0.4 to 4 dS/m, sodium adsorption ratio (SAR) from 5 to 70 and TDS concentrations from 270 to 2720 mg/L (Rice et al., 2002). Significant discharge of saline-sodic waters risks considerable environmental impact such as reductions in native water qualities, increased erosion, increased soil salinization/sodification/waterlogging, and growth or survival impacts to both native and agricultural vegetation.

Consideration of these potential impacts led to the development of several recommended CBM water management options intended to diminish associated environmental risks (BLM, 2003). Primary among these options are the construction of infiltration/evaporation reservoirs, direct land applications using methods such as center-pivot or side-roll irrigation systems or "mister" evaporation systems, and reinjection. Options for direct discharges of CBM water to streams and draws are restricted by regulatory requirements and related water treatment costs associated with multiple small production areas spread across large geographic regions. Several limitations have restricted CBM water reinjection in the PRB including desired beneficial use of co-produced water in these arid environments, economic considerations, and development patterns that allow CBM production from multiple mineral owners/producers on multiple coal seams within close proximities, thus creating the high likelihood that reinjection will significantly impact CBM production capabilities on adjacent properties. Therefore, the most common CBM water management options currently used in the PRB are infiltration/evaporation reservoirs and direct land application. Use of the former option is impacted by topographic considerations, cost of development, associated environmental impacts from extensive surface disturbance, groundwater monitoring responsibilities, contamination risks to shallow aquifers and existing surface springs, and requirements for continuous infra-structure modifications and additions as well-field development moves away from reservoir locations. Direct land applications of saline-sodic CBM water also represent significant risk, primarily to the physical and chemical properties of poorly drained soils (e.g., those dominated by the high shrink/swell smectitic clays common in the PRB (BLM, 2003)) and the vegetation communities that those soils support.

This paper discusses results from the first field season (2003) of research focusing on the use of direct land application to manage CBM co-produced water in the PRB. Study sites represent impacts from 1-3 years of saline/sodic CBM water application on variable vegetation types and soil textures, which include using various water and soil treatment strategies, land uses, and water application strategies. Risks associated with the environmental conditions and mitigating management strategies at our study sites are evaluated.

Methods and Materials

Geographic Study Area

The PRB is located in northeastern Wyoming and southeastern Montana, situated between the Black Hills on the east and the Big Horn Mountains on the west. It generally slopes northward from higher elevations in Wyoming towards the Yellowstone River in Montana, draining mainly via the Tongue and Powder Rivers to the north and the Belle Fourche and Cheyenne Rivers to the east. Ground-water flows are also northward with numerous coal seams being the most continuous water-bearing units. Shallow coal seams are readily tapped as water resources. Annual precipitation averages 38-43 cm along the periphery of the Basin and decreases to a low of 33 cm near its center with most of the precipitation coming between March and July. The climate is arid and semiarid with long, cold winters and short, hot summers. Soils are influenced by dominant local geologic conditions and vary in texture and quality accordingly. Soils are generally alkaline, low in organic matter content, and are often dominated by smectitic clays.

Land use is predominantly domestic livestock grazing and wildlife habitat, although farming is conducted along valleys with perennial streams that support irrigation (USDA-NRCS, 1998). Land uses and management status within the PRB are directly impacted by the mixed pattern of Federal, State, Tribal, and Private surface ownership that complicates regulatory over-site and CBM co-produced water management options associated with CBM development (Fig. 2).

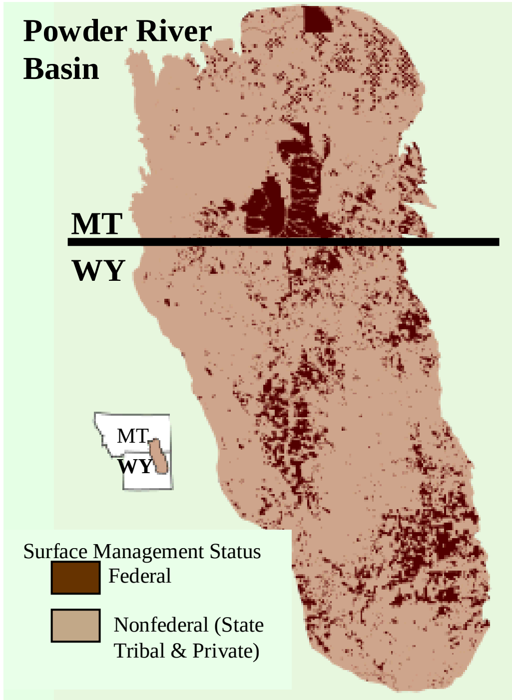

Figure 2. Surface Management Status, in the Powder River Basin (USGS, 2003).

Study Sites

Six study sites that had previously received CBM water applications over periods ranging up to 3 field seasons were evaluated for impacts to soil physical/chemical properties and several vegetation characteristics. These sites are located in Johnson and Sheridan Counties, Wyoming (Fig. 3). Soil types/textures, vegetation dominance, CBM water qualities/application rates, chemical treatment strategies (soil and water), and land uses are among the factors that vary between these sites (Table 1). CBM water is usually applied from May to November.

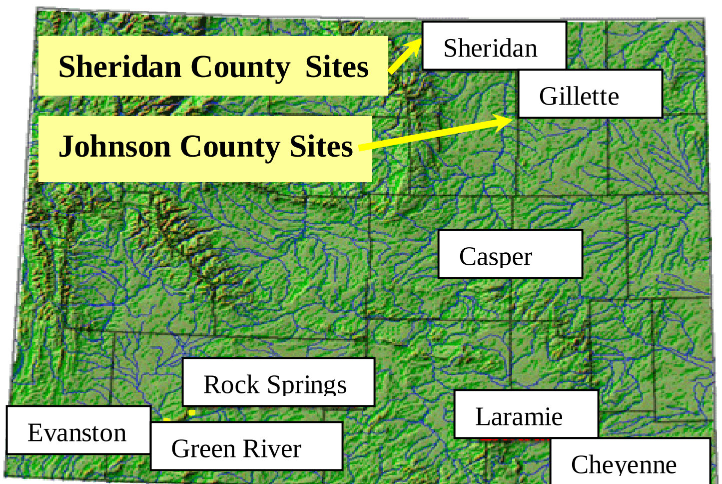

Figure 3. Wyoming general study site locations.

Table 1. Study sites characteristics and treatment procedures.

Site ID No./ seasons CBM Water Appl.	County loc./ Average Ann. Ppt.	CBM Water Appl. & Treatment Methods	Soil Amendments & Appl. Frequency	Vegetation Type/ dominant species/ land use[4]
1 /3	Johnson/25-38 cm	Center Pivot/water not treated	Surface application. Gypsum/Sulfur [2]	Seeded perennial grasses/western wheatgrass/**A**
2/<1[1]	Johnson/25-38 cm	Center Pivot/Zeolite	none	Seeded 2003/ germinating oats/**A**
3/3	Sheridan/38-43 cm	Side Roll/Sulfur Burner	Surface application. Gypsum/Sulfur [3]	Native grassland /needle and thread grass/**C**
4 /2	Sheridan/38-43 cm	Center Pivot/Sulfur Burner	Surface application. Gypsum/Sulfur [3]	Hayfield/Alfalfa & intermediate wheatgrass/**B**
5/2	Sheridan/38-43 cm	Side Roll/Sulfur Burner	Surface application. Gypsum/Sulfur [3]	Hayfield/Smooth Brome & alfalfa/**B**
6/3	Sheridan/38-43 cm	Side Roll/Sulfur Burner	Surface application. Gypsum/Sulfur [3]	Native grassland/ western wheatgrass/**C**

[1]CBM water application delayed until October, 2003.
[2]Amendment applications repeated through season as determined by soil SAR and EC sampling.
[3]Amendment was a single application in prior season.
[4]Land uses indicated as: **A**-Seeded vegetation functioning primarily as biological mitigation to CBM water effects (harvested once seasonally by haying or grazing); **B**-Seeded vegetation used for commercial hay production (multiple seasonal harvests); **C**-Native vegetation subject to grazing by domestic livestock and wildlife.

Soil Field Measurements

Soil samples from all 6 treated sites (receiving CBM water) and 5 adjacent, non-treated control sites were collected from 5 sample holes per site at 6 depth intervals (0-5, 5-15, 15-30, 30-60, 60-90, 90-120 cm). Soil samples were placed in resealable plastic bags to prevent moisture loss and transported to the laboratory for further analyses. Soil bulk densities were determined in 5 locations within each site at 3 depths (0-5, 5-15 and 15-30 cm) using the Core Method as described by Grossman and Reinsch (1999). Surface infiltration rates in treated and control sites were determined at 5 locations within each site by using the Single-Ring Infiltrometer Method (Reynolds et al., 1999). Hydraulic conductivity in treated and control fields were determined with the Auger Hole Method (Amoozegar et al., 1986), using 3 reps each of holes augered to 4 separate depths (15, 30, 60 and 90 cm). Holes were filled with water to saturate the soil, left over-night and then refilled the following day prior to recording readings.

Water Sampling

Coalbed methane water samples were collected from either reservoirs or sprinklers at these sites during June-July 2003 and refrigerated (~ $2^{o}C$) until analyzed for pH, EC, and SAR.

Laboratory Analyses

Soil sub-samples were oven-dried at 105°C to constant weight. Soil moisture contents were determined using differences between wet-weight and oven-dry weight. The depth with maximum moisture content was assumed to be the wetting front.

Soil samples were air dried, passed through a 2 mm sieve and analyzed for chemical properties. Soil textures were determined using the Hydrometer Method (Gee and Bauder, 1986), soil saturation paste extracts were prepared using the method described by Rhoades (1999), pH and EC values for saturation paste extracts and CBM water samples were determined using pH and EC meters, respectively (Thomas, 1999; Rhoades, 1999). Soluble Ca, Mg and Na concentrations in saturation paste extracts and CBM water samples were determined using Inductively Coupled Plasma Spectrophotometry (Suarez, 1999).

Sodium Adsorption Ratio (SAR) of saturation paste extracts and water samples was calculated using the following equation:

$$SAR = Na^{+} / [(Ca^{++} + Mg^{++})/2]^{0.5} \qquad \textbf{(1)}$$

where Na, Ca and Mg represent concentrations in milliequivalents per liter of the respective ions.

Vegetation Sampling

Vegetation measurements evaluated included above ground biomass, aerial cover, total number of species, arbuscular mycorrhizae (AM) fungi infectivity, and forage quality analyses. The last two parameters were only measured on selected perennial species.

Above ground Biomass, Aerial Cover, and Species Numbers. These parameters were measured on sites 1 and 3, both which are dominated by native perennial grass species [site 1—a seeded community of western wheatgrass (*Elymus smithii*) (Rydb.) Gould; site 3—a native community dominated by needle and thread grass (*Hesperostipa comata*) (Trin. & Rupr.) Barkw. and western wheatgrass]. Other sites were commercially harvested hayfields (sites 4 & 5), newly seeded with poor vegetation establishment (site 2), or without a representative plant community on the control area (site 6) and were not analyzed for these parameters. Production was determined by clipping 3 randomly located 0.5 m^2 rectangular plots on treated and control areas. Clippings were separated by life-form, oven-dried and weighed. Aerial cover was estimated using 5 randomly located 50 m line transects, read every m using the point-intercept method (first hit species were recorded). The number of species encountered on these transects were used to directly compare species numbers between treated and control.

Mycorrhizae Infectivity. Arbuscular mycorrhizae (AM) infectivity rates were evaluated on 3 species from site 3. Five individuals each of western wheatgrass, needleandthread, and blue grama (*Bouteloua gracilis*)(H.B.K.) Lag.ex Griffiths were randomly selected from both the treated and the control site and placed in resealable plastic bags. Plant root specimens were washed, clipped, and placed in 6.45 cm^2 biopsy cassettes for staining using a mixture of trypan blue, lactic acid, glycerol, and water. Following de-staining, roots were cut into ~2 cm segments and mounted on microscope slides with glycerol for AM infectivity estimates using a transect counting method for each slide.

Forage Quality Analyses. Crude fiber analyses (acid detergent fiber—ADF and neutral detergent fiber—NDF) were conducted on 8 vegetation species collected selectively from sites 1, 3, 4 and 5. Analyses were conducted using procedures recommended for the ANKOM Fiber Analyzer (ANKOM Technology, 2003).

Statistical Analysis

Significant differences between treated and control areas for different soil and vegetation parameters were determined by carrying out paired t-test of means. All tests for significance were determined using $P = 0.05$, unless otherwise noted.

Results and Discussion

CBM Water Chemistry

Results of CBM water analyses from our study sites are presented in Table 2. All EC and SAR values exceed minimum values (EC of 0. 75 dS m^{-1}; SAR of 10) generally considered to be non-problematic for irrigation water (U.S. Salinity Laboratory Staff, 1954; Warrence et al., 2002). Water qualities from our sites are consistent with those previously reported for CBM waters in the PRB (Rice et al., 2002; BLM, 2003).

Table 2. Selected chemical properties of CBM water samples from study sites.

Parameter	Site1	Site 2	Sites 3/6[2] Reservoir/sprinkler	Site 4	Site 5	Average	Range
pH	8.1	ND[1]	7.0/8.8	8.7	7.9	8.1	7.0 - 8.8
EC (dS m^{-1})	2.1	ND[1]	2.4/2.2	2.0	4.0	2.5	2.0- 4.0
SAR	29	ND[1]	23/31	38	15	27.2	15 – 38

[1]Not Determined; [2]These sites use the same water source. It was sampled from both the holding reservoir and sprinkler.

Soil Physical Properties

Soil Texture. Soil texture data and average percent clay content from 6 sample depths on treated and control sites are listed in Table 3. Except for site 1, treated areas at the 0-5 cm sample interval were coarser-textured with less clay content than non-treated controls. Overall clay content was greater than 20% on all sites at all depths except for treated site 3 (0-5 and 15-30 cm) and treated site 4 (90-120 cm), reflecting the influences of inter-bedded sedimentary sandstone parent material on those two sites. High clay content in the top 120 cm of these soils increases the likelihood of restricted water permeability and reduces the potential for leaching excess Na^+ (applied with the CBM water) out of plant rooting zones. Differences in soil textures between treated and control areas were not statistically significant.

Bulk Density. A summary of early season (June/July) and end of season (October) bulk density values for the upper 3 sample depths (0-5, 5-15, and 15-30 cm) on all sites is shown in Table 4. End of season bulk density values for control sites were obtained only on site 1.

Table 3. Texture of soil samples collected from different depths in irrigated and control sites.

Depth (cm)	Site 1 Trted./Cont % clay	Site 2 Trted./Cont. % clay	Site 3 Trted./Cont. % clay	Site 4 Trted./Cont. % clay	Site 5 Trted./Cont. % clay	Site 6 Trted/Cont. % clay
0-5	CL/CL 37/30	CL/SiCL 30/37	SL/loam 15/26	loam/CL 26/36	CL/clay 37/42	SCL/CL 22/36
5-15	clay/clay 49/41	CL/loam 30/27	SL/CL 22/33	CL/CL 29/40	clay/clay 41/47	SCL/CL 50/40
15-30	clay/CL 48/36	CL/CL 29/37	SCL/CL 17/32	CL/clay 38/48	clay/clay 42/44	clay/clay 50/48
30-60	clay/CL 41/35	loam/CL 26/40	SL/CL 26/33	CL/clay 39/53	clay/CL 42/39	clay/clay 36/53
60-90	CL/CL 37/40	CL/CL 28/33	SL/CL 32/29	SCL/clay 30/58	CL/CL 38/39	clay/clay 48/58
90-120	SCL/CL 32/38	loam/CL 22/40	SL/CL 29/29	SL/clay 16/43	CL/CL 36/36	clay/clay 58/43

Trted = treated area; Cont. = control area; CL =clay loam; SiCL= silty clay loam; SCL=sandy clay loam; SL=sandy loam.

At least two significant aspects of soil bulk density are related to management decisions regarding direct application of CBM water. First, bulk density measurements reflect the amount of pore space available in any given soil, which also impacts soil hydraulic conductivity. Compacted soils with high bulk density values are less permeable to water flows and less likely to support substantial profile leaching and Na^+ salt removal. Clay particle dispersion from saline-sodic CBM water applications and the subsequent leaching of these particles to sub-surface layers may be a factor creating denser horizons. Second, the ability to maintain healthy vegetation communities is one indicator of a healthy soil ecosystem. The ability of plant roots to penetrate soil is dependent on soil strength as controlled by bulk density and moisture content. Plant root penetration is generally not impeded at bulk densities of less than 1.3 g cm^{-3}, but can be greatly reduced when bulk density exceeds 1.4 g cm^{-3} during dry conditions. The same soil when moist, however, may not impede rooting because of decreased soil strength (Relf, 1997).

Interpreting bulk density effects between treated and control sites is therefore complicated by soil moisture content differences inherent to our sampling methodology (treated sites were moist/wet when sampled; control sites were generally dry). However, all bulk density values from treated sites at depths greater than 5 cm (5-30 cm) exceeded 1.4 g cm^{-3} and most exceed

1.5 g cm^{-3} indicating severe resistance to plant root penetration. Understanding the relationships between soil moisture content, saline-sodic effects, bulk density, and the ability of plant roots to penetrate the compacted rooting zones dominating these treated sites is critical to proper application of saline-sodic CBM water.

Table 4. Early and end of season bulk density (g cm^{-3}); 0-5, 5-15, and 15-30 cm sample depths.

Depth (cm)	Site 1 Trted/Cont	Site 2 Trted/Cont	Site 3 Trted/Cont	Site 4 Trted/Cont	Site 5 Trted/Cont	Site 6 Trted/Cont
Early Season – June/July						
0-5	1.4/1.4	1.1/1.0	1.4/1.4	1.4/1.3	1.1/1.3	1.1/1.3
5-15	1.7/1.5	1.4/1.4	1.6/1.6	1.5/1.3	1.5/1.5	1.4/1.3
15-30	1.6/1.6	1.4/1.4	1.6/1.5	1.6/1.1	1.7/1.6	1.8/1.1
End Season - October						
0-5	1.4/1.0	ND	1.2/ND	1.6/ND	1.0/ND	1.3/ND
5-15	1.7/1.3		1.5/ND	1.5/ND	1.4/ND	1.7/ND
15-30	1.6/1.4		1.5/ND	1.6/ND	1.5/ND	1.7/ND

Trted = treated area; Cont = control area; ND = Not Determined.

Infiltration Rates. Except for site 2 (CBM water application delayed in 2003) and site 3 (coarse-textured), infiltration rates for control sites were generally greater than those for CBM treated areas (Fig. 4). Applications of water with high Na^+ concentrations can result in clay dispersion and clogging of soil pores and lead to reduced soil permeability and water infiltration (U.S. Salinity Laboratory Staff, 1954; Aggasi et al., 1981; Bauder and Brock, 1992; Hergert and Knudsen, 1997).

Site 3 results emphasize the importance of soil texture in determining site suitability for direct applications of saline-sodic CBM water. Other factors influencing infiltration rates at these sites include soil bulk density, soil moisture amounts and distribution in the profile, soil physical and chemical characteristics, topography, water application rates, water chemical characteristics, soil and ambient air temperatures and season of application. Differences in infiltration rates were statistically significant only for site 5.

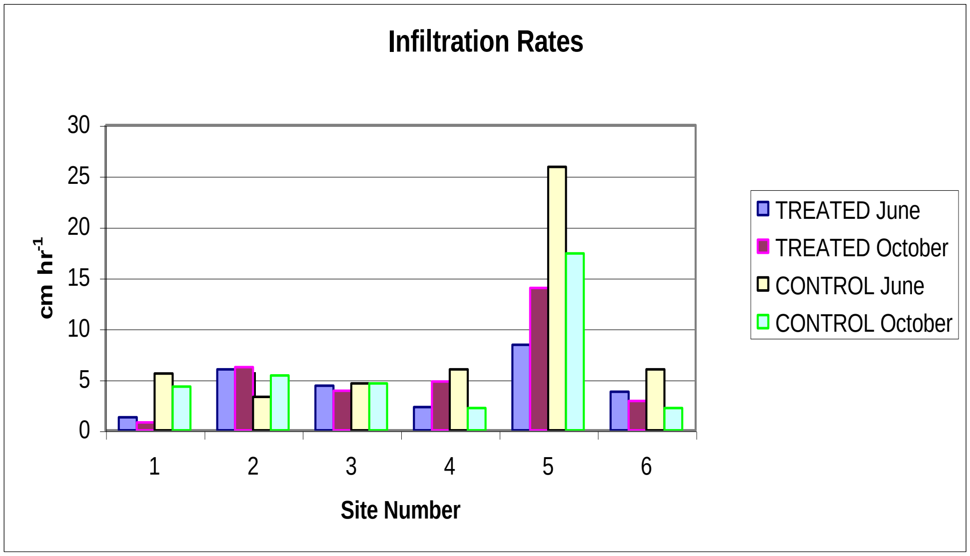

Figure 4. Infiltration rates (cm hr^{-1}) in CBM treated and control areas.

Hydraulic Conductivity. Hydraulic conductivity (HC) measures water flow velocities under saturated conditions within a soil profile. Differences in HC between treated and control areas were only significant ($p = 0.05$) on site 1. However, all control site HC's were consistently greater than treated site HC's (Figure 5). Although clay dispersion from saline-sodic CBM water application is suspected to be at least partially responsible, it is not clear why HC's would be reduced at soil depths up to 90 cm when moisture penetration as indicated by the wetting front was not measured deeper than 60 cm. Further analyses are needed to address this question.

Soil Chemical properties

Soil pH, EC, and SAR values at 6 sample depths up to 120 cm are listed in Table 5 with significant differences noted between control and treated sites. Data are from early season (June-July) 2003. Salinity measurements (EC) in soils receiving CBM water applications (treated sites) indicate that salt accumulations are occurring in the upper 3 sample depths (above 30 cm). It is noteworthy that sites 1 and 3 also have significant salt accumulations to depths of at least 120cm. Site 1 is operated under an intense water application management strategy that annually applies CBM water at a rate of about 90 cm (compared to about 45 cm for sites 3-6). This may indicate that the greater water load (in association with an intense regime of surface chemical applications of gypsum and elemental sulfur (S)) is allowing salts to leach deep into this soil profile despite

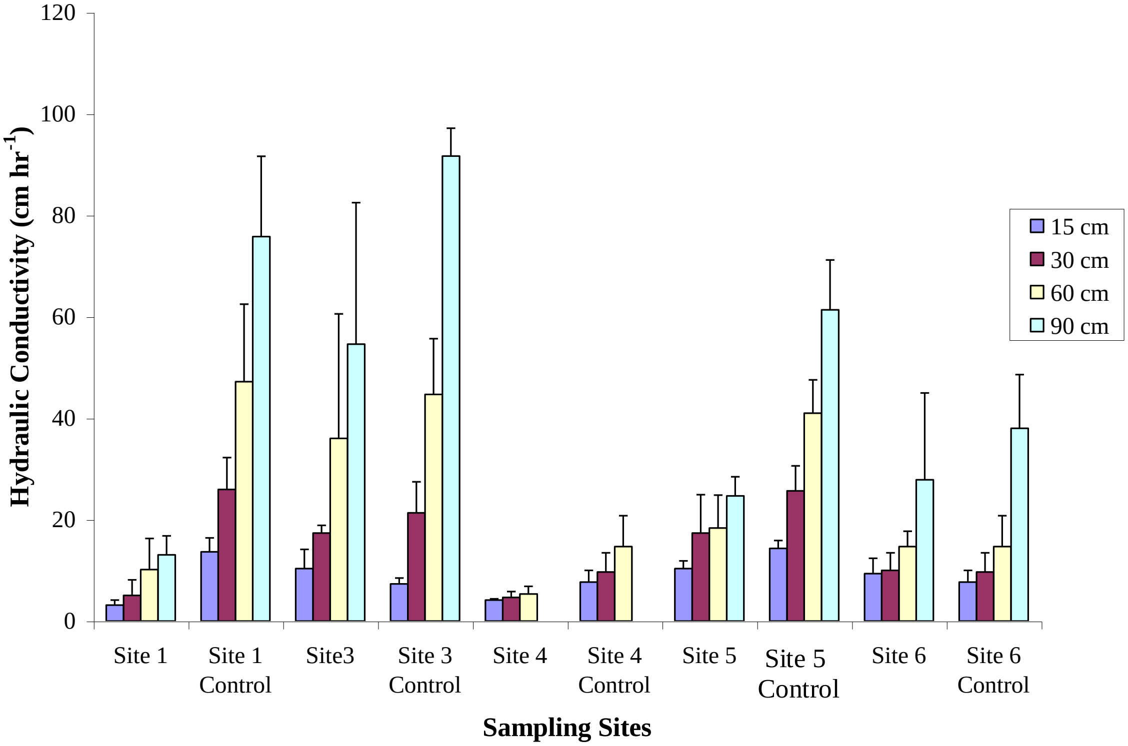

Figure 5. Soil hydraulic conductivity (cm hr^{-1}) at different depths in treated and control areas.

high clay contents (Table 3) and bulk densities (Table 4). Although site 3 receives less CBM water, it still appears to be accumulating salts at depth; a relationship probably associated with the relatively unrestricted water movements common to sandy loam soil textures (Fig. 4 and 5). Soil SAR values tend to mirror the EC patterns, generally reflecting greater values on sites treated with saline-sodic CBM water applications.

Vegetation Measurements

Biomass production, vegetation aerial cover, and species numbers from sites 1 and 3 are summarized in Tables 6 and 7. AM fungi infectivity rates on 3 native grass species from site 3 are listed in Table 8.

Table 5. Early season soil pH, EC (dS/m^{-1}) and SAR parameters by depth.

Site &	Treated Sites (depths in centimeters)						Control Sites (depths in centimeters)					
parameter	0-5	5-15	15-30	30-60	60-90	90-120	0-5	5-15	15-30	30-60	60-90	90-120
Site 1 pH	7.6[a]	7.6	7.5	7.6[a]	7.8	7.9	8.1[b]	7.8	7.8	7.9[b]	8.0	8.1
EC[ab]	7.13	5.93	5.39	2.53	1.09	2.16	0.64	0.37	0.37	0.39	0.41	0.70
SAR	15.0[a]	20.3[a]	13.0[a]	4.1[a]	4.2	5.1	5.1[b]	1.7[b]	0.9[b]	0.4[b]	0.4	1.9
Site 2pH[1]	8.1	8.1	8.1	8.1	8.0	7.9	8.1	8.2	8.1	8.0	7.8	7.8
EC	0.98	0.84	0.8	1.4	3.91	5.71	2.33	0.69	2.48	0.95	5.37	6.35
SAR	1.6	1.2	2.0	3.4	7.4	8.6	0.2	0.3	0.6	2.0	4.8	6.4
Site 3 pH	7.9	8.2	8.2	8.2	8.1	8.0	8.3	8.2	8.0	8.1	8.0	7.8
EC[ab]	1.86	1.04	0.99	1.48	4.09	4.99	1.14	0.53	0.42	0.77	1.45	3.6
SAR	7.3	6.3	5.9	4.5	5.3	7.1	3.2	3.9	2.4	1.9	3.2	4.4
Site 4 pH	7.7[a]	7.7[a]	7.6[a]	7.6[a]	7.9	8.0	8.1[b]	8.2[b]	8.1[b]	8.2[b]	8.0	8.0
EC[ab]	3.80	1.39	1.30	1.21	0.56	0.41	0.72	0.45	0.4	0.49	1.66	2.78
SAR	4.5[a]	3.5	3.6	0.7	0.6	0.4	1.9[b]	2.5	2.2	3.0	3.0	2.7
Site 5 pH	7.9	8.4	8.2	8.3	8.2	8.2	8.0	8.2	8.3	8.3	8.3	8.3
EC	2.76[a]	1.48	0.91	0.82	0.76	0.78	0.91[b]	0.75	0.80	0.88	0.75	0.78
SAR	7.8[a]	6.9	5.4[a]	4.3[a]	2.9	4.4	0.6[b]	1.6	1.6[b]	1.8[b]	1.8	1.7
Site 6 pH	7.9	8.2	8.1	8.2	8.1	8.1	8.1	8.2	8.1	8.2	8.0	8.0
EC[ab]	1.91	1.11	1.10	1.72	4.23	5.49	0.72	0.45	0.40	0.49	1.66	3.41
SAR	9.0	9.1[a]	8.2	4.5	4.1	6.2	1.9	2.5[b]	2.2	3.0	3.0	3.1

[1] CBM water application delayed until Oct. 2003. [a]Small letters indicate significance (*P*=0.05) for parameters at common depths between corresponding treated and control sites. [ab]These parameters were significant at all common depths between corresponding treated and control sites.

Table 6. Vegetation production comparisons from sites 1 and 3.

	Treated (kg/ha)	Control (kg/ha)
Site 1		
perennial grass	2538	194
annual grass	0	64
perennial forb	trace	25
annual forb	0	31
TOTAL	2539	314
Site 3		
perennial grass	730	685
annual grass	65	260
perennial forb	3	5
annual forb	5	9
shrub	3	39
TOTAL	806	998

Biomass Production, Vegetation Aerial Cover, Species Numbers. Biomass production from native perennial grass species on treated sites 1 and 3 exceeded that of control sites after 2-3 seasons of CBM water application (Table 6). However, total vegetation production on site 3 control exceeded that of the treated site (Table 6).

Vegetation aerial cover increased with CBM-water application on both sites 1 and 3 (Table 7). However, aerial cover provided by non-perennial grass species decreased with CBM water application, although no affect on the total number of species present on site 3 was measured (Table 7).

Table 7. Vegetation aerial cover and species numbers comparisons from sites 1 and 3.

	Site 1				Site 3			
	TREATED*		CONTROL*		TREATED*		CONTROL*	
VEGETATION LIFE FORM	% cover	# species	% cover	# species	% cover	# species	% cover	# species
perennial grasses (sedge)	95.5%	2	46.5%	6 (1)	75.5%	7 (1)	51.0%	6 (1)
annual grasses	0.0%	0	9.0%	3	9.2%	2	15.0%	2
perennial forbs	0.5%	1	1.0%	2	2.0%	1	0.5%	1
annual forbs	0.0%	0	5.0%	3	1.0%	2	2.0%	4
shrub	0.0%	0	5%	1	1.0%	2	14%	1
succulents	0.0%	0	2.5%	1	0.0%	0	0.0%	0
litter	1.5%		17%		5.6%		12.5%	
rock	0.5%		0.0%		0.5%		1.0%	
bare ground	2.0%		14.0%		5.2%		4.5%	
Total Vegetation Cover	96.0%		69.0%		88.7%		82.0%	
Total Cover & no. of species	100%	3 total	100%	17 total	100%	15 total	100%	15 total

*n=5

Vegetation management concerns regarding land application of CBM waters include potential changes in relative composition and dominance of vegetation communities from differential tolerances of individual species to altered conditions. Both the biomass production data and the vegetation cover data reflect differential responses among vegetation life forms to saline-sodic CBM water applications. Modifications in vegetation community structures following several years of CBM water application will have a direct impact of the reclamation potential of these lands when CBM water applications are stopped. It is well known that plant diversity is a key component of enhancing reclamation success. Treatments that threaten to reduce plant species (or life-form) diversity also risk diminishing reclamation potential and should be closely monitored to ensure ecosystem impacts do not become irreversible.

AM Fungi Infectivity Rates. Arbuscular mycorrhizae infectivity rates on two perennial grass species, needle and thread and western wheatgrass, were significantly higher (P=0.05) on treated sites (Table 8). Infectivity rates on blue grama were also higher on treated sites, but this difference was not significant. These infectivity increases are consistent with the biomass and aerial cover data that indicate a positive response of native perennial grasses to CBM water applications. Symbiotic AM fungi are common on native range plants, but responses of these relationships to enhanced environmental stresses associated with the increased soil salinity and Na^+ concentrations that accompany CBM water applications have not been well studied. AM fungi function to enhance nutrient uptake in plants and infectivity rates have been shown to be reduced under conditions of adequate plant nutrient availability (e.g., agricultural fertilization). Our data indicate an increased infectivity rate that may be positively associated with increased water availability. Another possible interpretation could be that increased plant stresses related to nutrient uptake (associated with modifications in soil water osmotic potentials) may have facilitated the increase in AM infectivity rates. However, EC and SAR values from surface sample depths on this coarse-textured site do not indicate salt accumulations to support this interpretation.

Table 8. Arbuscular mycorrhizae (AM) fungi infectivity rates of selected native grasses following 2 years of CBM water application.

SPECIES	TREATED average % of roots infected	CONTROL average % of roots infected
blue grama	44%	41%
needle and thread	62% [a]	39% [b]
western wheatgrass	68% [a]	40% [b]

[a]Values followed by different letter are significantly different at P = 0.05 level.

Forage Digestibility. Results of forage digestibility analyses (ADF and NDF) on selected vegetation species subjected to CBM water application were inconsistent. Factors other than saline-sodic CBM water applications may be impacting these responses, such as frequency of grazing/cutting, inherent nutritional variations between varieties of species, age of plants at harvest, and moisture stress factors on plants sampled from control areas.

Conclusions

Field studies identifying vegetation and soil impacts from land application of saline-sodic waters in the PRB are limited. Supplemental water applications in these environments risk disruption of natural soil water balances with subsequent impacts on soil ecological, physical, chemical and hydrological characteristics, all of which strongly influence vegetation communities and reclamation potentials. Current land application scenarios include the use of CBM water on agricultural lands (primarily alfalfa or grassland pastures) using methods, rates and timing consistent with standard production agricultural practices; and application of CBM waters to non-cultivated, diverse, native rangeland communities often without consideration to the physiological water needs of native species. Indications of potential impacts to soil physical (increased bulk densities, decreased infiltration and hydraulic conductivity rates) and chemical (increased EC and SAR values, particularly above 30 cm in the soil profiles) properties following 1 to 3 years of saline-sodic CBM water applications emphasize the need to continue to seek improvements in water management strategies that will minimize these impacts. This is particularly true when consideration is given to impacts on native vegetation communities (differential tolerances between species to saline-sodic CBM water applications) and the resulting impacts to long-term reclamation potentials of lands supporting native communities once CBM water application is discontinued. More focus should be given to water application management on these sites appropriate for the physiological needs of native vegetation. Lands being managed for commercial agricultural interest (i.e., alfalfa hayfields) have already developed histories of water and soil nutrient management consistent with the needs of plant production. Additionally, the need to apply these management practices is a generally accepted concept by agriculturists. While its true that applications of saline-sodic CBM water to these lands will create additional impacts to both soil and vegetation, implementation of management plans intended to address these impacts may be more readily accepted than those proposed for native plant communities. It will be important to develop successful CBM water management strategies that fit both scenarios in order to minimize overall impacts of CBM development in the PRB.

Acknowledgments

Authors acknowledge the financial support provided by Bureau of Land Management (BLM) for carrying out this research project. Study site availability and access were kindly provided by J. M. Huber Corporation, Williams Production Company and Anadarko Petroleum Corporation. Laboratory assistance for characterizing AM fungi was kindly provided by Dr. Peter Stahl.

References

Agassi, M. I., Shainberg, I., and I. Morin. 1981. Effect of electrolyte concentration and soil sodicity on infiltration rate and crust formation. Soil Sci. Soc. Am. J. 45:848-851. http://dx.doi.org/10.2136/sssaj1981.03615995004500050004x.

Amoozegar, A., Warrick, A. W. and A. Klute. 1986. Chapter 29. Hydraulic Conductivity of Saturated Soils: Field Methods. p. 735-770. *In* Arnold Klute (ed.) Methods of Soil Analysis Part 1, Physical and Mineralogical Methods, second edition. Am. Soc. Ag. and Soil Sci. Soc. Am. publisher, Madison, WI.

ANKOM Technology. 2003. Method for determining acid detergent fiber and neutral detergent fiber. Available at http://www.ankom.com/09_procedures/procedures1.shtml (verified12/17/2003).

Bauder, J. W. and T. A. Brock. 1992. Crop species, amendment, and water quality effects on selected soil physical properties. Soil Sci. Soc. Am. J. 56:1292-1298. http://dx.doi.org/10.2136/sssaj1992.03615995005600040047x.

Bauder, J. W. and T. A. Brock. 2001. Irrigation Water Quality, Soil Amendment, and Crop Effects on Sodium Leaching. Arid La. Res. Manage. 15:101-113. http://dx.doi.org/10.1080/15324980151062724.

Bureau of Land Management (BLM). 2003. Final environmental impact statement and proposed plant amendment for the Powder River Basin soil and gas project. Volumes 1-3. Buffalo Field Office, Buffalo, WY.

Gee, G. W. and J. W. Bauder. 1986. Chapter 15. Particle-Size Analysis. p. 383-411. *In* Arnold Klute (ed.) Methods of Soil Analysis Part 1, Physical and Mineralogical Methods, second edition. Am. Soc. Ag. and Soil Sci. Soc. Am. publisher, Madison, WI.

Grossman, R. B. and T. G. Reinsch. 2002. Chapter 2.1. Bulk Density and Linear Extensibility. p. 201-228. *In* Jacob H. Dane and G. Clarke Topp (ed.) Methods of Soil Analysis Part 4, Physical Methods. Am. Soc. Ag. and Soil Sci. Soc. Am. publisher, Madison, WI.

Hergert, G. W. and D. Knudsen. 1997. Irrigation water quality criteria. Cooperative Extension, Institute of Agriculture and Natural Resources, University of Nebraska-Lincoln. Available at http://www.ianr.unl.edu/pubs/water/g328.htm 5 p. (verified 12/17/2003).

Pinkser, L.M. 2002. Coalbed Methane: The Future of U.S. Natural Gas? Geotimes, November Issue. Available at http://www. geotimes. org/nov02/resources. html (verified 10/10/2003).

Relf, D. 1997. Managing Compacted and Heavy Soils. Virginia Cooperative Extension, Available at http://www.ext.vt.edu/departments/envirohort/factsheets3/soils/JUL93PR1.HTML (verified 12/17/2003).

Reynolds, W. D., D. E. Elrick, and E. G. Youngs. 2002. Chapter 3.4.3.2.a Single-Ring and Double- or Concentric-Ring Infiltrometers. p. 821-826. *In* Jacob H. Dane and G. Clarke Topp (eds.) Methods of Soil Analysis Part 4, Physical Methods. Am. Soc. Ag. and Soil Sci. Soc. Am. publisher, Madison, WI.

Rhoades, J. D. 1996. Chapter 14. Salinity: Electrical Conductivity and Total Dissolved Solids. p. 417- 436. *In* D. L. Sparks, A. L. Page, P. A. Helmke, R. H. Loeppert, P. N. Soltanpour, M. A. Tabatabai, C. T. Johnston, and M. E. Sumner (eds.), Methods of Soil Analysis Part 3, Chemical Methods. Am. Soc. Ag. and Soil Sci. Soc. Am. publisher, Madison, WI.

Rice, C.A., T. T. Bartos, and M. S. Ellis. 2002. Chemical and Isotopic composition of water in the Fort Union and Wasatch Formations of Powder River Basin, Wyoming and Montana: Implications for Coalbed Methane Development. p. 53-70. *In* S. D. Schwochow and V.Nuccio, (eds.) Coalbed Methane of North America II. Rocky Mountain Association of Geologists Volume. 108 p.

Saurez, D. 1996. Chapter 20. Beryllium, Magnesium, Calcium, Strontium, and Barium. p. 575-602. *In* D. L. Sparks, A. L. Page, P. A. Helmke, R. H. Loeppert, P. N. Soltanpour, M. A. Tabatabai, C. T. Johnston, and M. E. Sumner (eds.), Methods of Soil Analysis Part 3, Chemical Methods. Am. Soc. Ag. and Soil Sci. Soc. Am. publisher, Madison, WI.

Thomas, G.W. 1996. Chapter 16. Soil pH and Soil Acidity. p. 475-490. *In* D. L. Sparks, A. L. Page, P. A. Helmke, R. H. Loeppert, P. N. Soltanpour, M. A. Tabatabai, C. T. Johnston, and M. E. Sumner (eds.), Methods of Soil Analysis Part 3, Chemical Methods. Am. Soc. Ag. and Soil Sci. Soc. Am. publisher, Madison, WI.

U.S. Department of Agriculture, Natural Resource Conservation Service (USDA-NRCS). 1998. Soil Survey of Sheridan County Area, WY.

U.S. Department of Energy, Office of Fossil Energy (USDE-OFE). 2002. DOE study raises estimates of Coalbed methane potential in Powder River Basin. Available at http://fossil.energy.gov/news/techlines/02/tl_cbm_powderriver.html. (verified 12/17/2003).

U.S. Geological Service (USGS). 2003. Powder River Basin federal surfaces management. Available at http://geology.cr.usgs.gov/energy/fedland/FS12-98/fig6a.gif (verified 12/17/2003).

U.S. Salinity Laboratory Staff (USDA). 1954. Diagnosis and improvement of saline and alkali soils. USDA Agric. Handbook. No. 60. U.S. Gov. Print. Office. Washington, D.C.

Warrence, N., J. W. Bauder, and K. E. Pearson. 2002. Basics of salinity and sodicity effects on soil physical properties. Department of Land Resources and Environmental Sciences, Montana State University-Bozeman, MT.

Wheaton, J.R. and J.J. Metesh. 2002. Potential ground-water drawdown and recovery for coalbed methane development in the Powder River Basin, Montana. Montana Bureau of Mines and Geology Open-File Report 458:58 p.

Wyoming Oil and Gas Conservation Commission. 2003. Web page summary path: county, well summary, Campbell/Converse/Johnson/Sheridan. Available at http://wogcc.state.wy.us. (verified 9/30/2003).