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IMPACTS OF LAND APPLICATION OF SALINE-SODIC COALBED METHANE WATER ON SOIL PHYSICAL AND CHEMICAL PROPERTIES IN WYOMING[1]

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Abstract: Changes in soil physical and chemical properties due to land application of coalbed methane (CBM) waters were investigated in study sites located in northwest Powder River Basin (PRB) of Wyoming. Samples of CBM water used for land application and analyzed for pH, electrical conductivity (EC), and sodium adsorption ratio (SAR) values. Water quality data indicated that EC and SAR values of CBM water samples were greater than the recommended values for irrigation use (0.75 dS m^{-1} and <10 SAR). Impacts of these poor-quality CBM waters on soil physical and chemical properties were evaluated by collecting soil samples during the 2003 irrigation season from 6 depths (0-5, 5-15, 15-30, 30-60, 60-90 and 90-120 cm) from 6 sites that received CBM water applications for up to 3 years, which were compared to control sites. Changes in soil physical (e.g., infiltration rates, bulk density) and soil chemical (pH, EC, and SAR of saturation paste extracts) properties were determined. Our study indicates that the pH values are significantly ($p = 0.05$) greater in irrigated plots than control plots at depths of 0-5 and 30-60 cm in site 1 and 0-60 cm in site 4. The EC values were significantly greater in irrigated sites than control plots at 0-60 cm depth in sites 1, 4 and 6, 5-30 cm in site 3, and 0-15 cm in site 5. SAR values were significantly greater in irrigated sites than control plots in the upper 60 cm in sites 1 and 5, 0-5 cm site 4, and 5-30 cm in site 6. Irrigated sites 1, 3, and 4 had significantly lower %clay. Hydraulic conductivity in sites 1 and 5 were significantly lower than control plots. Thus, irrigation with poor-quality CBM water had significant impacts on soil chemical and physical properties. It has been estimated that over the next 15 years CBM 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 CBM waters and to develop possible mitigating criteria for preserving impacted PRB ecosystems.

Key Words: Soil, CBM Water, Sodium, Salinity, SAR, PRB, Wyoming

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Introduction

Natural gas (i.e., Methane) is an important source of energy for residential and industrial sectors in the U.S. One of the important sources of natural gas in the country is the methane produced from coal seams, which currently accounts for 9% of country's natural gas production (Pinkser, 2002). Several areas within the U.S. produce coalbed methane (CBM), of which the Powder River Basin (PRB), covering parts of Wyoming and Montana, is the most active area. Coalbed methane production involves pumping water (hereafter referred to as CBM water) from coal seams to reduce hydrostatic pressure to facilitate methane exploration. A single CBM well can discharge water between 4 and 100 liters per minute (lpm). Depending upon the local conditions and production rates, a CBM well may be productive for 2 to 20 years, with an average lifespan of 7 years. At present there are over 20,000 CBM wells permitted or drilled in the PRB region and it is estimated that another 50,000 to 100,000 new wells will be drilled in the future. The total CBM water production in the PRB is expected to peak at about 47,000 ha-m in 2006 and the cumulative CBM-water production during the period 2002-2017 is estimated to be 366,000 ha-m (BLM, 2003).

The quality of CBM water is variable within the region and is often not suitable for direct irrigation. CBM water 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, SAR from a low of 5 to extreme high of 70 and total dissolved solids (TDS) concentrations from 270 to 2720 mg/L (Rice et al., 2002). Application of CBM waters with high salinity (e.g., EC) can result in reduced water uptake and water stress to plants due to increased energy requirements for plants to obtain soil water (Burrow et al., 2002). While tolerance to salinity varies among crop types, it is generally accepted that saline conditions have negative impacts on all crops. High saline levels can result in toxicity of certain ions such as chloride (Cl^-), Na^+, and boron (B) to plants. At higher pH, availability of micronutrients such as iron (Fe), copper (Cu), zinc (Zn) and manganese (Mn) will be reduced. In addition, salinity can affect soil physical properties. Salinity increases flocculation of clay particles resulting in aggregation, increased permeability and aeration, and better root growth and penetration; however, sodicity has the opposite effect on soils. Sodium causes dispersion of soil clay particles and organic matter, resulting in surface crusting, reduced infiltration and reduced hydraulic conductivity (Park and O'Connor, 1980).

Soils in the PRB region are dominated by smectitic clays, and nearly 41% of the PRB area is covered with soils characterized by poor drainage (BLM, 2003). Application of saline-sodic CBM water on land with limited drainage and dominated by smectitic clays can have negative impacts on soil physical and chemical properties. Irrigation with saline-sodic waters can result in reduced soil quality that could lead to poor vegetation growth, eventually rendering the soil susceptible to erosion. In order to avoid permanent damage to the fragile rangeland ecosystem, a good understanding of potential impacts of saline-sodic CBM water application on soil physical and chemical properties is important. A field study was conducted to better understand impacts of CBM water irrigation on soil properties during the 2003 irrigation season. The main objectives of the study were to: (i) evaluate the quality of CBM water and (ii) examine changes in soil physical and chemical properties due to land application of CBM waters.

Methods and Materials

Study Area

The PRB, located in northeast Wyoming and southeast Montana (Figure 1), is situated

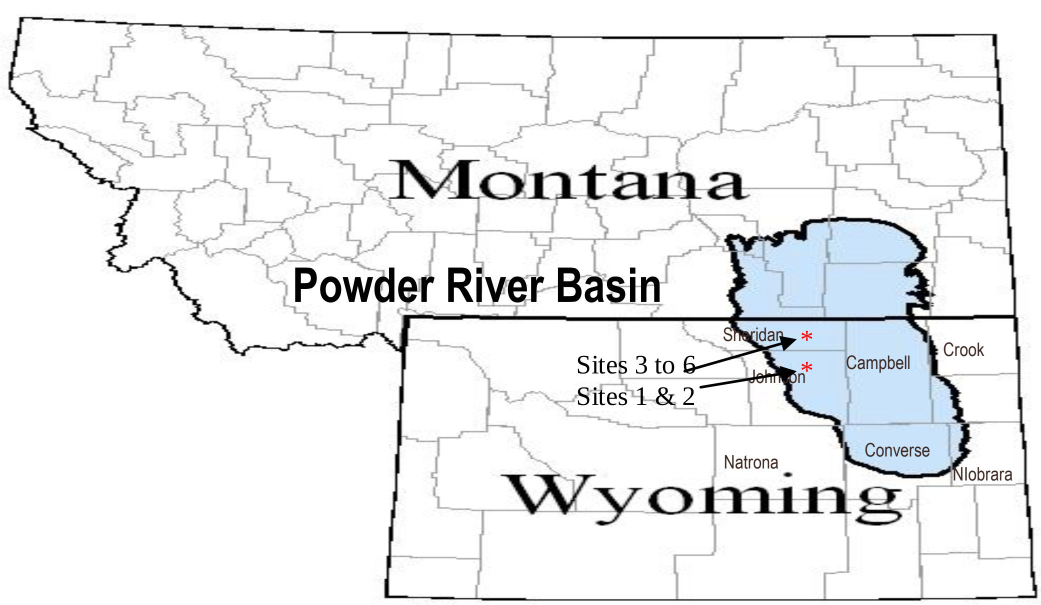

Figure 1. Powder River Basin (PRB), covering parts of Wyoming and Montana, contains extensive coal reserves. The CBM activities in the PRB in Wyoming are currently the most active in the U.S.

between the Black Hills to the east, the Big Horn Mountains to the west and the Miles City Arch to the north. Land surface generally slopes northward from higher elevations in Wyoming and drains to the Yellowstone River in Montana. The Tertiary Fort Union Formation and the overlying Wasatch Formation are dominated by bedrock exposures in Montana. In Wyoming the Wasatch Formation is widely exposed at the surface. The Tongue River Member of the Fort Union Formation contains coal that is mined in both states and is the source unit for CBM. Montana's coalbeds are shallower than Wyoming's, and exposures along valley and canyon walls enhance methane (CH_4) leaking to the atmosphere. Ground-water flow in the PRB is generally from the south to the north. Coal seams are the most continuous water-bearing units and provide an important ground-water resource. Shallow coal seams are readily tapped as water resources.

Soils of the PRB have developed under a climatic regime characterized by cold winters, warm summers and low to moderate precipitation (e.g., rainfall of 30 to 38 cm and snowfall between 91-152 cm). Soil textures vary and are influenced by dominant geologic conditions. Wide exposures of the Wasatch formation in Wyoming have led to the development of soils reflecting its sandy character. In Montana, geologic parent materials dominated by interbedded claystone and sandstone units of the Tongue River Member have developed soils that are typically finer textured with higher clay content. Soils are generally alkaline and low in organic matter. Farming is conducted along valleys with perennial streams that support irrigation.

Study sites, Water and Soil Sampling

Six sites that have received CBM water over a period of up to 3 years (irrigation seasons) were selected to evaluate impacts on soil physical and chemical properties. These sites are located in Johnson and Sheridan counties in Wyoming (Fig. 1). The dominant vegetation types on the irrigated and control sites are listed in Table 1.

Table 1. Details of dominant vegetation in study sites.

	Irrigated	Control
Site 1	western wheatgrass (*Pascopyrum smithii*)	Sagebrush (*Artemisia tridentata ssp. wyomingensis)*, western wheatgrass and bluegrama (*Bouteloua gracilis*)
Site 2	Oats (*Avena sativa*) and western wheatgrass	western wheatgrass
Site 3	needleandthread (*Stipa comata*) and western wheatgrass	needleandthread and sage brush
Site 4	alfalfa(*Medicago sativa*)	alfalfa
Site 5	smooth brome (*Bromus inermis*)	smooth brome and alfalfa
Site 6	needleandthread and western wheatgrass	western wheat grass and sage brush

Study sites are irrigated with CBM water between May and November. At present study sites are being managed by different CBM Gas Companies. Details of the study sites are summarized in Table 2.

Table 2. Details of water application methods, water treatments, soil treatments and years of water application in the study sites.

Site No	County	Water Application Method	Water Treatment Before Irrigation	Soil Treatment and/or Amendments	Years of irrigation
1	Johnson	Center Pivot	None	Surface application of Gypsum and Sulfur	3
2	Johnson	Center Pivot	Zeolite	None	<1 Delayed until Oct 03
3	Sheridan	Side Roll	Sulfur Burner	Surface application of Gypsum and Sulfur	3
4	Sheridan	Side Roll	Sulfur Burner	Surface application of Gypsum and Sulfur	2
5	Sheridan	Center Pivot	Sulfur Burner	Surface application of Gypsum and Sulfur	2
6	Sheridan	Side Roll	Sulfur Burner	Surface application of Gypsum and Sulfur	3

Samples of CBM water used at these sites were collected in plastic bottles during June-July 2003 and stored refrigerated until analyzed for chemical properties. To evaluate the impacts of CBM water irrigation on soil properties, 5 random soil samples from 6 depths (0-5, 5-15, 15-30, 30-60, 60-90, and 90-120 cm) were collected from each of the irrigated and control sites (adjacent to irrigated sites with same soil types). Samples were stored in re-sealable plastic bags to prevent moisture loss during transportation to the laboratory for further analysis.

Field Measurements

Bulk Density. Soil bulk density was determined in 5 locations within each site at 3 depths (0-5, 5-15 and 15-30 cm) by using the Core Method described by Grossman and Reinsch (1999).

Infiltration rates. Field site infiltration rates were determined at 5 locations within each site by the Single-Ring Infiltrometer method (Reynolds et al., 1999).

Hydraulic Conductivity. Hydraulic conductivity was determined by using the Auger Hole Method (Amoozegar et al., 1986). At each site, 3 auger separate holes were drilled for each of the 4 different depths (15, 30, 60 and 90 cm). The auger holes were filled with water on the previous day to saturate the soil and readings were taken after refilling the holes with water on the following day.

Laboratory Analyses

Sub-samples dried at 105°C to constant in weight and soil moisture content were used to determine the difference between field moist and oven-dry weight. The depth at which the moisture content was maximum was assumed to be the wetting front.

Soil samples were air dried, passed through a 2-mm sieve and analyzed for particle-size distribution and chemical properties. Soil texture was determined by using the Hydrometer Method (Gee and Bauder, 1986). Soil saturation paste extracts were prepared by using the method described by Rhoades (1999). The 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 was calculated by using the formula given below:

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

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

Statistical Analysis

Significant differences between irrigated and control sites for different parameters were determined by carrying out two sample t-test for different parameters. All the tests for significance were carried out at p = 0. 05 unless otherwise mentioned in the text.

Results and Discussion

CBM Water Chemistry

Results of the CBM water analyses are presented in Table 2. The data show that the EC and SAR values for water samples were well above the desired EC level of 0. 75 dS m^{-1} and SAR value of 10 (U.S. Salinity Laboratory Staff, 1954). These results are in agreement with what has been reported in the literature on CBM water chemistry (Rice et al., 2002).

Table 2. Selected chemical properties of CBM water samples.

Parameter	Average	Range
pH	8. 2	7. 0 - 8. 9
EC (dS m^{-1})	2. 62	1. 83 - 3. 95
Ca (mg L^{-1})	15	4 – 24
Mg (mg L^{-1})	15	3 – 32
Na (mg L^{-1})	591	390 – 936
SAR	29	15 – 38

Impacts on Soil Physical Properties

Soil Texture. Soil textures of irrigated and control sites are listed in Table 3. Most irrigated site (except site 1) soil textures were coarser than the control sites. The differences in clay content of irrigated and control sites were statistically significant for site 1 for the top 15 cm, site 3 in the upper 15 cm and site 4 in the 15-30 cm depth. Except for site 1, the clay content in soil samples from sites that showed significant differences were lower than control sites. This may be attributed to dispersion of clay by high SAR CBM water and subsequent leaching of clay particles (Agassi et al., 1981), since these sites are continuously irrigated (some up to 91 cm in an irrigation season). In site 1, 5-15 cm depth samples showed significantly greater clay contents compared to control sites, which may be due to dispersion and leaching of clay from the surface to sub-surface soil horizons.

Table 3 Texture and clay content (%) of soil samples collected from different depths in irrigated and control sites (**Bold %clay** values indicate significant differences between irrigated and control sites).

	Depth (cm)	Irrigated-Texture (%Clay)	Control-Texture (%Clay)
Site 1	0-5	Clay Loam (**37**)	Clay Loam (**30**)
	5-15	Clay (**49**)	Clay (**41**)
	15-30	Clay (48)	Clay Loam (36)
	30-60	Clay (41)	Clay Loam (35)
	60-90	Clay Loam (37)	Clay Loam (40)
	90-120	Clay Loam (32)	Clay Loam (38)
Site 2	0-5	Clay Loam (31)	Silty Clay Loam (37)
	5-15	Clay Loam (30)	Loam (27)
	15-30	Clay Loam (29)	Clay Loam (37)
	30-60	Loam (29)	Clay Loam (40)
	60-90	Clay Loam (29)	Clay Loam (33)
	90-120	Loam (**23**)	Clay Loam (**40**)
Site 3	0-5	Sandy Loam (**15**)	Loam (**26**)
	5-15	Sandy Loam (**17**)	Clay Loam (**33**)
	15-30	Sandy Clay Loam (22)	Clay Loam (32)
	30-60	Sandy Loam (25)	Clay Loam (33)
	60-90	Sandy Loam (17)	Clay Loam (29)
	90-120	Sandy Loam (12)	Clay Loam (29)
Site 4	0-5	Loam (26)	Clay Loam (36)
	5-15	Clay Loam (29)	Clay Loam (40)
	15-30	Clay Loam (**38**)	Clay (**48**)
	30-60	Clay Loam (39)	Clay (53)
	60-90	Sandy Clay Loam (25)	Clay (56)
	90-120	Sandy Loam (20)	Clay (56)
Site 5	0-5	Clay Loam (37)	Clay (42)
	5-15	Clay (41)	Clay (47)
	15-30	Clay (42)	Clay (44)
	30-60	Clay (42)	Clay Loam (39)
	60-90	Clay Loam (38)	Clay Loam (39)
	90-120	Clay Loam (36)	Clay Loam (36)
Site 6	0-5	Sandy Clay Loam (22)	Clay Loam (36)
	5-15	Sandy Clay Loam (32)	Clay Loam (40)
	15-30	Clay (50)	Clay (48)
	30-60	Clay (52)	Clay (53)
	60-90	Clay (52)	Clay (56)
	90-120	Clay (56)	Clay (43)

Bulk Density. Bulk density values for the top 3 layers (0-5, 5-15, and 15-30 cm) in irrigated and control sites are shown in Fig. 2. Data indicate that bulk density values for irrigated site sub-soils were consistently greater than control sites, although the differences were statistically significant only in site 6. Irrigating soils with a high SAR irrigation water can increase Na^+ concentration in soil (Bauder and Brock, 2001). This could have resulted in clay dispersion and subsequent leaching of clay particles to subsurface layers leading to denser horizons. This observation is in agreement with the coarser texture surface horizons in CBM irrigated sites. Greater bulk densities in irrigated sites compared to control sites could also be due to swelling of clay (especially smectitic type found in PRB region) upon irrigation with CBM waters (Levy et al., 2002; Sirjacobs et al., 2001). However, paired t-test analysis indicated that the differences were not statistically significant, except for the 0-5 and 15-30 cm layers in site 6.

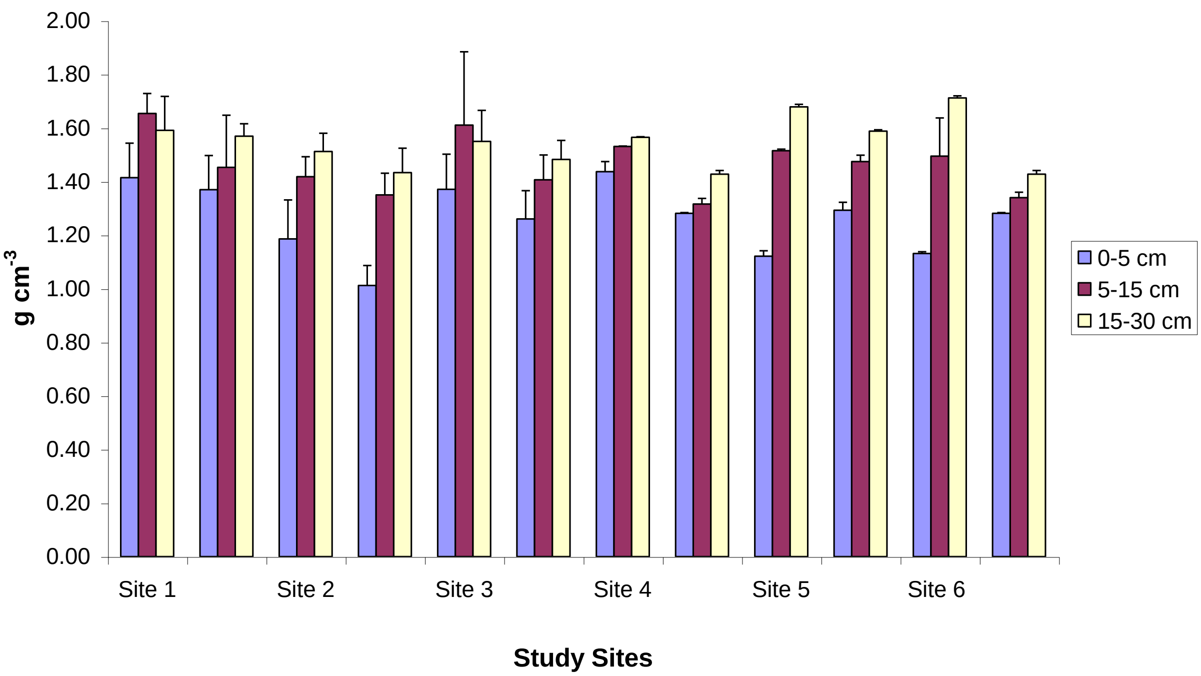

Figure 2. Bulk Density values for 0-5, 5-15, and 15-30 cm soil layers in CBM irrigated and control fields.

Infiltration Rate. Infiltration rates for control sites were consistently greater than CBM irrigated sites (Table 4). Soil infiltration rates are influenced by factors such as conditions of soil surface, physical and chemical nature of the soil profile and the distribution of moisture in the soil profile. Irrigating soils with high SAR CBM water may have resulted in clay dispersion and clogging of soil pores by clay particles. This would lead to the formation of "surface seal" and reduced infiltration (Agassi et al., 1981; Yu et al., 2003). Site 2 did not receive a complete round of CBM water irrigation, and the greater rate of infiltration compared to its control site is mainly because the irrigated site was plowed. Other irrigated sites did not differ significantly from control sites in infiltration rates.

Table 4. Infiltration rates (cm hr^{-1}) in CBM irrigated and control sites.

	Infiltration rate ± Std. Dev (cm hr^{-1})	Remarks
Site 1	1.8 ± 1.0	NS
Site 1 Control	5.6 ± 4.6	
Site 2	7.2 ± 2.1	*
Site 2 Control	3.3 ± 2.7	
Site 3	3.7 ± 2.4	NS
Site 3 Control	4.6 ± 1.9	
Site 4	2.3 ± 1.3	NS
Site 4 Control	6.1 ± 9.6	
Site 5	8.4 ± 5.4	NS
Site 5 Control	24.1 ± 16.1	
Site 6	3.8 ± 2.3	NS
Site 6 Control	6.1 ± 9.6	

NS: Not Significant, * Significant at $p = 0.05$

Hydraulic Conductivity. Hydraulic conductivity is the effective flow velocity of water in the soil profile under saturated condition (i.e., when the hydraulic gradient is 1). Fig. 3 shows that hydraulic conductivities of soils at different depths in control sites were consistently greater than CBM water irrigated sites. Though differences in hydraulic conductivity rates were statistically significant for site 1 for all the depths (15, 30, 60 and 90 cm), and site 5 at 15, 60 and 90 cm depths, the general trend of reduced hydraulic conductivity in CBM irrigated sites is evident. Blockage of soil pores and aggregate destabilization as a result of clay dispersion and movement are the main mechanisms responsible for reduction in hydraulic conductivity in soils irrigated with high SAR (Na^+) irrigation waters (Park and O'Connor, 1980).

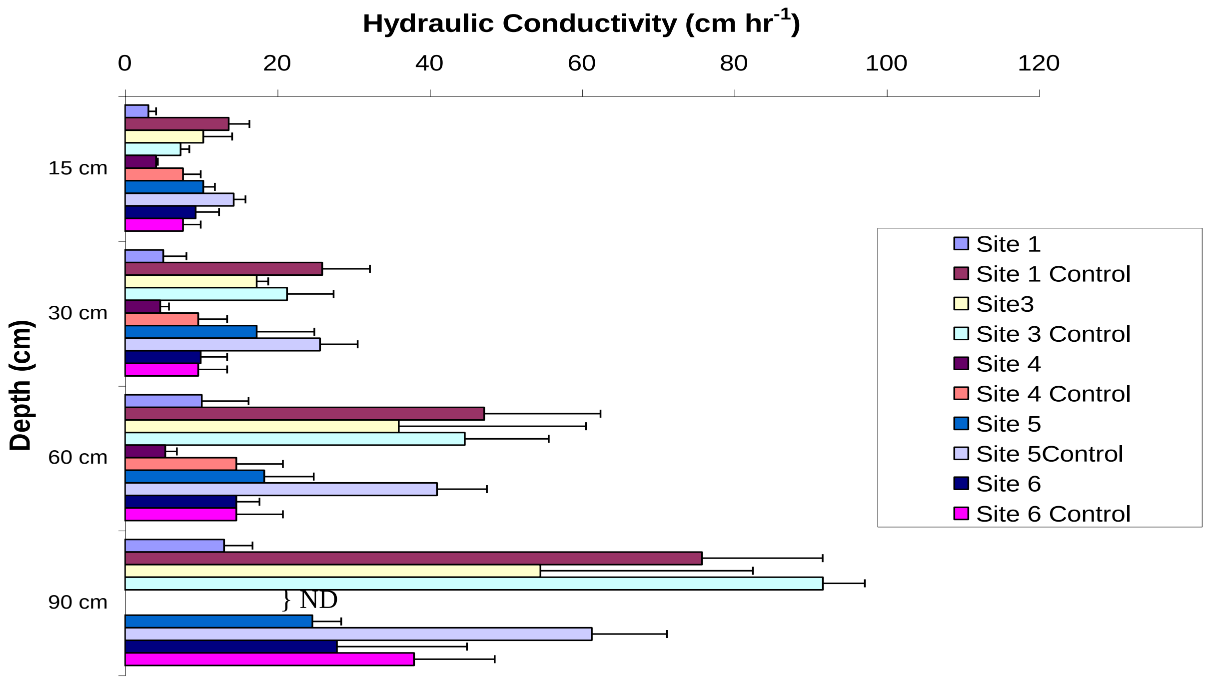

Figure 3. Hydraulic conductivity (cm hr^{-1}) of soil at different depths in CBM irrigated and control fields (Error bars represent Standard Deviation of means).
ND- Not Determined

Impacts on Soil Chemical properties

Soil pH. The pH values of soil samples from different depths ranged from 7.5 to 8.4 (Table 5) with pH values that were significantly different between irrigated and control sites in two sites, site 1 (0-5 cm and 30-60 cm) and site 4 (top 60 cm). Soil pH data indicate the presence of neutral salts in these soils.

Table 5. Soil pH values at different depths in CBM irrigated and control sites.

Study sites	Depth	Irrigated	Control	Remarks
Site 1	0-5 cm	7.6 ± 0.2	8.1 ± 0.3	*
	5-15 cm	7.6 ± 0.2	7.8 ± 0.3	NS
	15-30 cm	7.5 ± 0.1	7.8 ± 0.2	NS
	30-60 cm	7.6 ± 0.2	7.9 ± 0.2	*
	60-90 cm	7.8 ± 0.1	8.0 ± 0.2	NS
	90-120 cm	7.9 ± 0.2	8.1 ± 0.2	NS
Site 2	0-5 cm	8.1 ± 0.2	8.1 ± 0.2	NS
	5-15 cm	8.1 ± 0.2	8.2 ± 0.3	NS
	15-30 cm	8.0 ± 0.2	8.1 ± 0.2	NS
	30-60 cm	8.1 ± 0.2	8.0 ± 0.2	NS
	60-90 cm	8.0 ± 0.2	7.8 ± 0.2	NS
	90-120 cm	7.9 ± 0.1	7.8 ± 0.1	NS
Site 3	0-5 cm	7.9 ± 0.5	8.1 ± 0.2	NS
	5-15 cm	8.2 ± 0.4	8.2 ± 0.1	NS
	15-30 cm	8.3 ± 0.1	7.9 ± 0.5	NS
	30-60 cm	8.1 ± 0.2	8.0 ± 0.3	NS
	60-90 cm	8.1 ± 0.1	7.9 ± 0.5	NS
	90-120 cm	7.9 ± 0.3	7.7 ± 0.5	NS
Site 4	0-5 cm	7.7 ± 0.1	8.1 ± 0.2	*
	5-15 cm	7.7 ± 0.2	8.2 ± 0.2	*
	15-30 cm	7.6 ± 0.1	8.1 ± 0.1	*
	30-60 cm	7.6 ± 0.2	8.2 ± 0.3	*
	60-90 cm	7.9 ± 0.1	8.0 ± 0.3	NS
	90-120 cm	8.0 ± 0.2	8.0 ± 0.3	NS
Site 5	0-5 cm	7.9 ± 0.1	8.0 ± 0.3	NS
	5-15 cm	8.4 ± 0.2	8.2 ± 0.1	NS
	15-30 cm	8.2 ± 0.3	8.3 ± 0.2	NS
	30-60 cm	8.3 ± 0.1	8.3 ± 0.2	NS
	60-90 cm	8.2 ± 0.1	8.3 ± 0.2	NS
	90-120 cm	8.2 ± 0.1	8.3 ± 0.2	NS
Site 6	0-5 cm	7.9 ± 0.2	8.1 ± 0.2	NS
	5-15 cm	8.2 ± 0.5	8.2 ± 0.3	NS
	15-30 cm	8.1 ± 0.2	8.1 ± 0.1	NS
	30-60 cm	8.2 ± 0.3	8.2 ± 0.3	NS
	60-90 cm	8.1 ± 0.2	8.0 ± 0.3	NS
	90-120 cm	8.1 ± 0.3	8.0 ± 0.3	NS

NS- Not Significant; * - Significant at $p = 0.05$

<u>*Soil Salinity*</u>. Soil electrical conductivity (EC) is the most widely used measure of salinity. Soils with saturation paste extract EC (EC_e) of 4 dS m^{-1} are considered to be saline (U. S. Salinity Laboratory Staff, 1954). In the present study, sites 1 and 5 were saline, whereas sites 3 and 4 are potentially saline (Fig. 4). Within site 1, soil up to 30 cm was saline and in site 5 only the 0-5 cm soil was saline.

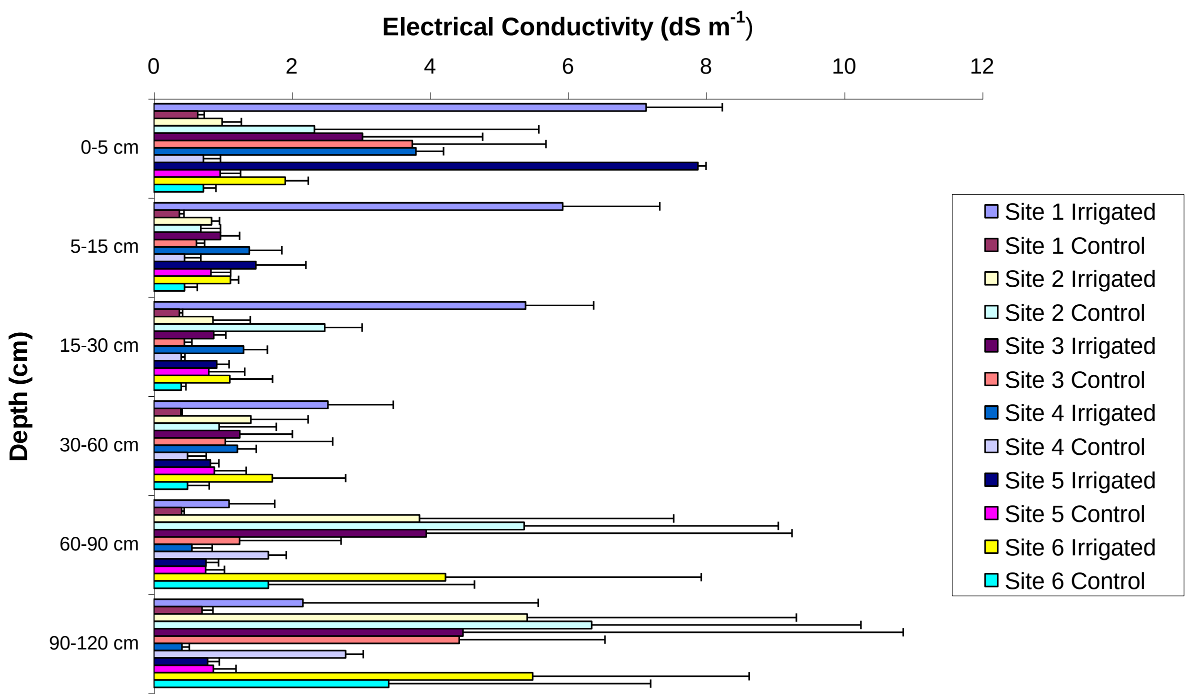

Figure 4. Soil saturation paste extract EC (EC_e) at different depths in CBM irrigated and control fields (Error bars represent Standard Deviation of Means).

Differences in EC_e between CBM irrigated and control sites were significant in sites 1 (top 60 cm), 3 (5-60 cm depth), 4 (top 60 cm), 5 (0-15 cm) and 6 (top 60 cm). There were no significant differences between irrigated and control soils at site 2 because of limited irrigation. Fig. 4 indicates that salt accumulation decreased with depth (up to 30 cm) in irrigated sites. This could be due to build of salts in surface layers from irrigation with saline-sodic CBM water. Data on soil moisture content (not presented) at the time of sampling indicated that the wetting front in most of irrigated sites was within 30-60 cm. Upon irrigation, with the downward movement of CBM water, salts will also leach to sub-surface horizons where it will accumulate. Data also show that efforts by different gas companies to move salts in CBM irrigated sites (as a result of salt addition due to saline-sodic CBM water irrigation) below root zone have not yielded the desired results.

Sodicity. The SAR values of CBM irrigated soil saturation paste extracts were consistently greater than that of control sites except at site 2 (Fig. 5). Differences in SAR values between

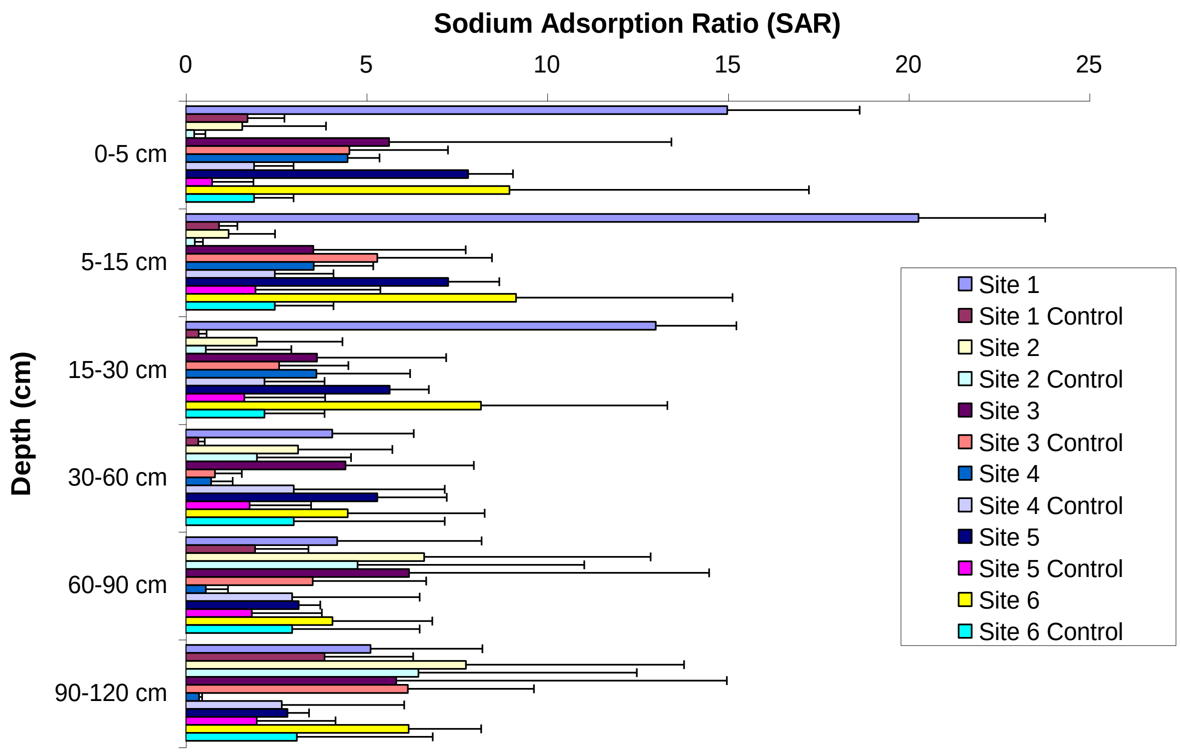

Figure 5. Sodium Adsorption Ratios values for saturation paste extracts of soil samples collected from different depths in CBM irrigated and control fields.

irrigated and control sites were statistically significant for the upper 60 cm in sites 1 and 5, 0-5 cm in site 4, 5-15 and 15-30 cm in site 6. In site 2, which has not received one complete irrigation season of CBM water and site 3 which has sandy loam soil, irrigated and control sites SAR values were not statistically significant. The increase in SAR values confirm the accumulation of Na in CBM irrigated soils as a result of irrigation with poor quality water. The results also confirm that build up of Na^+ is more pronounced in fine texture soils (site 1) than coarse texture soils (site 3). Accumulation of Na in surface layers in most irrigated sites might be due to a combination of Na^+ addition through CBM water and concentration of salts through evapo-transpiration within the root zone (Burrow et al., 2002).

Conclusions

This study confirmed that CBM water being used for irrigation in the study area is of poor quality and unsuitable for direct irrigation. Suitable precautionary measures and proper treatment of CBM water are necessary before it should be used for irrigation and or land disposal. Results of our study indicate steady buildup of salts and Na in the surface soil layers, resulting in reduced infiltration rates and hydraulic conductivity in sites irrigated with CBM waters. Though differences between irrigated and control sites are more pronounced in sites that have fine textured soils that were subjected to longer periods of CBM water irrigation, trends of salt and Na accumulation and deterioration in soil physical properties in other sites evaluated in this study are clear. The results of the present study show that irrigation or land disposal of poor quality (saline-sodic) CBM water on soil in the absence of proper ameliorating measures (water and soil treatments) can potentially have serious negative impacts on fragile cropland and rangeland ecosystems in the PRB. It is expected that CBM production will continue to develop at a rapid rate, creating economic benefits and extensive impacts on the PRB environment. Addressing these impacts in a meaningful way will require continued data collection through monitoring of CBM production and recovery responses and on-going research projects.

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