LAND APPLICATION OF COALBED METHANE PRODUCED WATER: CHANGES IN SOIL CHEMISTRY THROUGH TIME[1]

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Abstract. Federal and State agencies, special interest groups, energy companies, and the public debate the methods used to manage groundwater produced through coalbed natural gas (CBNG) operations. Coalbed natural gas produced water is unaltered groundwater that is typically sodium bicarbonate rich. A ten-step plan has been developed to irrigate six sites in the Powder River Basin of northeastern Wyoming with CBNG produced water for multiple irrigation seasons. A combination of techniques, referred to as managed irrigation, were used to maintain soil chemical conditions that are supportive of plant growth. To prevent excessive salinity accumulation in the plant root zone, soil water balances and irrigation scheduling were used to maintain suitable agronomic leaching fractions. Geochemical equilibrium modeling determined the quantity of soil-applied amendments, used to mitigate the sodicity hazard of CBNG produced water. Since the initiation of irrigation, soil sampling occurred in each of the six fields at least bi-annually. Results indicate that soil electrical conductivity (EC), exchangeable sodium percentage (ESP), and sodium adsorption ratio (SAR) have increased significantly since the initiation of irrigation due to the application of both produced water and soil applied amendments. Soil pH has not increased appreciably compared to adjacent non-irrigated areas. The presence of well-aggregated soil structure and stable soil infiltration rates; which do not differ significantly from adjacent non-irrigated areas, suggest sodic soil conditions are not present. Although soil EC, ESP, and SAR have increased, management strategies have prevented the formation of sodic soil conditions. Agronomic leaching has maintained root zone salinity at levels suitable for moderately tolerant plant species, which are native to northeastern Wyoming.

Additional Key Words: land management, low quality irrigation water, and northeastern Wyoming

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[1] Paper was presented at the 2009 National Meeting of the American Society of Mining and Reclamation, Billings, MT, ***Revitalizing the Environment: Proven Solutions and Innovative Approaches*** May 30 – June 5, 2009. R.I. Barnhisel (Ed.) Published by ASMR, 3134 Montavesta Rd., Lexington, KY 40502.

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Proceedings America Society of Mining and Reclamation, 2009 pp 921-947
DOI: 10.21000/JASMR09010921
http://dx.doi.org/10.21000/JASMR09010921

Introduction

In the western United States, and elsewhere, coalbed natural gas (CBNG) production has increased to satisfy the growing demand for clean, readily available energy. In 2006, the Powder River Basin (PRB, Fig. 1) of Wyoming produced approximately 9.6 billion cubic meters of CBNG from 17,200 wells (WOGCC, 2007) or roughly twenty percent of the CBNG produced in the United States (EIA, 2007a). The PRB contains an estimated 69.3 billion cubic meters of recoverable CBNG reserves (EIA, 2007b).

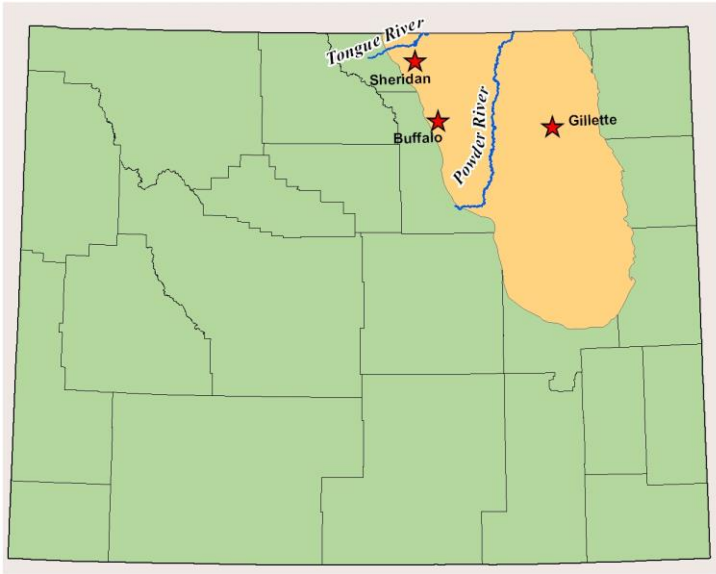


Figure 1. Powder River Basin (PRB) of Wyoming.

During CBNG production, operators pump water from coal seams to reduce the hydrostatic pressure and subsequently release methane. Water production peaks during the early phases of CBNG extraction and declines through time (Rice et al., 2000). The amount of water (produced water) generated during CBNG production ranges from 8 to 80 L min^{-1} (Patz et al., 2004). The rate varies widely depending upon production phase, well density, and aquifer characteristics. In 2006, CBNG production in the PRB yielded 11,000 ha-m of produced water (WOGCC, 2007).

As CBNG production continues within the PRB, water management strategies are increasingly important issues debated by the public, Federal and State agencies, special interest groups, and energy companies. Within the semi-arid PRB, irrigation with CBNG produced water could increase forage crop yields. If successful, land application of CBNG produced water may prove to be a cost effective and beneficial use of industrial water.

However, the chemistry of CBNG produced water presents a significant challenge for irrigation. Within the PRB, CBNG produced water is moderately saline and sodium bicarbonate rich. Rice et al. (2000) observed that within the frequently targeted Wyodak-Anderson coal seam, sodium (Na) and bicarbonate (HCO_3^-) concentrations in produced water tend to increase from south to north and from east to west within the PRB. Subsequent research (McBeth et al., 2003; Patz, 2004) supports this trend. Long-term trends of CBNG produced water quality are difficult to predict. Recent research in the PRB indicates that salinity, as measured by electrical conductivity (EC), and Na adsorption ratio (SAR) of produced water ranges from 0.4 to 4.4 dS m^{-1} and 6 to 69, respectively (Table 1).

Long-term application of CBNG produced water to soils, without treatment, poses both a salinity and sodicity hazard. The formation and behavior of sodic, saline-sodic, and saline soil is well-documented (Sumner, 1993; Sumner and Naidu, 1998; Levy, 2000). As are techniques to ameliorate or reclaim such soils (Qadir, 2001). Although the use of low quality water is expected to increase (Qadir, 2001), the long-term effects of the on-going use of both low-quality waters and soil amendments are poorly understood. Without this pertinent information, land managers must design their own strategies to use low-quality waters and amendments while preserving soil physical and chemical conditions that are supportive of long-term productivity. This paper summarizes the process of managed irrigation with CBNG produced water and presents case studies from managed irrigation sites.

Managed Irrigation: Materials and Methods

Managed irrigation is a beneficial use of CBNG produced water that employs soil science, water chemistry, agricultural engineering, and agronomic principles to maintain soil physical and chemical conditions that are supportive of plant growth. Managed irrigation with CBNG produced water requires comprehensive planning that includes the following steps:

Step 1: Irrigation Water Quality Assessment

CBNG water quality assessments are a crucial part of both the initial planning phase and an on-going monitoring activity during operation. Evaluation of salinity, sodicity, alkalinity, and specific ion toxicity occurs according to guidelines presented in Ayers and Westcot (1985) and Hansen et al. (1999).

Table 1. Selected chemical parameters of CBNG produced waters from the Powder River Basin.

					Anions		**Cations**		
		pH	**EC**	**SAR**	**HCO_3^-**	**SO_4^{2-}**	**Ca^{2+}**	**Mg^{2+}**	**Na^+**
Source		s.u.	dSm^{-1}		mgL^{-1}	mgL^{-1}	mgL^{-1}	mgL^{-1}	mgL^{-1}
USGS 2006	low	6.6	0.42	5.6	290	<0.03	1.8	0.6	110
	high	8	4.4	69	3,140	530	78	46	1,100
	average*	7.3	1.6	20	1,280	5.4	29	6	430
Rice et al 2000	low	6.8	0.57	5.7	290	<0.01	5.9	1.6	110
	high	7.7	3.0	32	2320	12.0	69	46	800
	average†	7.3	1.3	12	950	2.4	32	16	300
McBeth et al 2003	low	7.1	0.94	9.5	—	0.2	8.4	21	350
	high	7.4	2.6	17	—	2.6	59	29	410
	average‡	7.2	1.9	12	—	1.1	38	25	380
Patz et al 2004	average§	7.1	4.3	25	—	<0.1	49	32	930

Note: For each study the reported high, low, and average values are given for each parameter.
Abbreviations: SAR= sodium adsorption ratio, HCO_3^-= bicarbonate, SO_4^{2-}= sulfate
Source: modified from USGS 2006; Rice et al 2000; McBeth et al 2003; and Patz et al 2004
* Reported values are an average of 174 samples (n=174) from the Fort Union Formation.
EC calculated from TDS measurements based on Hansen et al (1993).
† Reported values are an average of 47 samples (n= 47) from through out the Powder River Basin.
‡ Reported values are an average of 14 samples (n= 14) from the Little Powder River Watershed.
McBeth et al (2003) calculated EC from TDS measurements based on Hansen et al (1993).
Reported SAR= SARp.
§ Reported values are an average of 24 samples (n= 24) from Burger Draw and Sue Draw.
Patz et al (2004) calculated EC from TDS measurements and ionic strentgh based on Griffin and Jurinak (1973). Reported SAR= SARp.

Salinity. The salinity of irrigation waters does not directly affect soil physical properties. Rather, saline irrigation waters may increase osmotic stress, which reduces the crop's ability to extract water from the soil (Ayers and Westcot, 1985). Crops vary with respect to salinity tolerance. Most forage crops grown in the PRB are moderately to highly tolerant to salt (Maas, 1990). The salinity of CBNG produced water from the PRB ranges from 0.4 to 4.4 dS m^{-1} (Table 1). This range illustrates the need for site and crop specific water quality assessments.

Sodicity. The key issue with respect to irrigation suitability of CBNG produced waters is the naturally occurring Na concentrations. Sodium adsorption ratio (SAR) assesses the sodicity hazard of potential irrigation waters. Sodium adsorption ratio is calculated with the following formula:

$$SAR = \frac{[Na^{+}]}{\sqrt{\left(\frac{([Mg^{2+}]+[Ca^{2+}])}{2}\right)}} \quad \textbf{(1)}$$

Where cation concentrations are in meq L^{-1}.

The SAR of produced water from the PRB ranges from 6 to 69 (Table 1). Soil infiltration and permeability decline in soils dominated with Na due to clay swelling and dispersion. The degree to which Na adversely affects a soil is dependent upon inherent soil properties and the concentration of other salts in the soil system (Levy, 2000). Thus, evaluation of the sodicity of irrigation water occurs in conjunction with the salinity (Ayers and Westcot, 1985; Hansen et al., 1999). The EC and SAR of most produced waters indicate that long-term irrigation with produced water may cause a slight to moderate reduction in soil infiltration capacity (Ayers and Westcott, 1985; Fig. 21). Therefore, land application of produced water typically requires water and or soil conditioning to mitigate the effects of the elevated SAR.

Alkalinity. The primary form of alkalinity in CBNG produced water is bicarbonate (HCO_3^-). Bicarbonate concentrations of CBNG produced water range from 290 to 3,140 mg L^{-1} (Table 1). At these concentrations, HCO_3^- reacts with soluble Ca and Mg to form Ca and Mg carbonates. Any reduction in soluble Ca and Mg concentrations will increase the SAR of CBNG produced water, and potentially any soil to which water is applied. Thus, HCO_3^- must be neutralized to maintain Ca solubility.

Specific Ion Toxicity. Sodium, chloride (Cl), and boron (B) can be toxic to certain crops if their concentrations become too high. In general, forage crops grown in the PRB are not especially sensitive to Na or Cl. Boron concentrations in produced water are typically low, often below detectable levels (Rice, 2000), and do not pose a toxicity risk.

Step 2: Project Water Balance

Accurate and detailed water balances are essential to all large-scale water management activities. Water production from CBNG wells is typically greatest during the initial phase of production. As production continues, the volume of water extracted tends to decline; the rate of decline depends on aquifer characteristics and well density (Rice et al., 2000). To estimate total produced water volume and timing, data from individual wells and field development activities are combined. As the project continues, more refined water balances relate CBNG produced water volume and rate to crop water use estimates, water storage requirements, and alternative water management strategies.

Step 3: Geochemical Modeling and Amendment Prescriptions

CBNG produced water typically requires treatment to reduce the SAR and neutralize HCO_3^- alkalinity that is present in the water. Two basic strategies reduce SAR - Na removal or Ca addition. Project economics typically favor Ca addition through gypsum ($CaSO_4 \cdot 2H_2O$) application to the water or soil, rather than Na removal via reverse osmosis or other treatments. Bicarbonate neutralization ensures that natural and added Ca remains soluble in the soil-water system and the pH of the soil is maintained. The preferred method to neutralize HCO_3^- is the addition of elemental sulfur (S) to the soil surface. Microbial oxidation converts S to sulfuric acid (H_2SO_4) as follows:

$$S + 1.5O_2 + H_2O \rightarrow H_2SO_4 \quad \textbf{(2)}$$

The rate of microbial oxidation is largely dependent upon soil temperature and soil moisture content (Sylvia et al 2005). Sulfur oxidation occurs steadily through out the growing season, which is more desirable than an instantaneous release. In the soil-water system, sulfuric acid (H_2SO_4) readily dissociates:

$$H_2SO_4 \rightarrow SO_4^{2-} + 2H^+ \quad \textbf{(3)}$$

Protons released in the above reaction neutralize HCO_3^-:

$$H^+ + HCO_3^- \rightarrow H2O + CO_2 \quad \textbf{(4)}$$

Other techniques, such as acid addition to the water or soil, and sulfur burners have substantial operational limitations.

PHREEQC (Pakhurst et al 2005), a multi-phase geochemical equilibrium model, is used to simulate water chemistry under various amendment or water blending scenarios. The simulations assume that all soil-applied amendments will dissolve over the course of the irrigation season. Simulations use a two-step approach. First, H_2SO_4 is incrementally added to the produced water to ensure that HCO_3^- is completely consumed. The stiochiometry of the above reactions (equations 2 through 4) determines the final quantity of S required to neutralize the HCO_3^-.

The second step supplies Ca through gypsum addition. Gypsum dissolution occurs as follows:

$$CaSO_4 \cdot 2H_2O \rightarrow Ca^{2+} + SO_4^{2-} + 2H_2O \qquad \textbf{(5)}$$

Soluble Ca reduces the SAR of the produced water or displaces Na from clay minerals. Gypsum is added until the SAR of the resultant water is less than specified management targets, typically a value less than 10.

The modeling results dictate the amendment rates. Soil applied amendments are prescribed on a ton per hectare per centimeter of water applied basis. Amendment rates are adjusted for product purity and may include a multiplier for imperfect field applications. The gypsum amendments are often industrial by-products with a purity of greater than 90 percent. Sulfur amendment are typically agricultural grade sulfur prills, but may also include sulfur-rich industrial by-products. The particle size of gypsum and sulfur amendments should not exceed 2 mm (Lebron et al., 2002). Amendment prescriptions occur for initial planning purposes and on an annual basis during managed irrigation operations.

Step 4: GIS-based Soil Screening

Initial identification of candidate irrigation sites occurs by using geographical information system (GIS) technology and published USDA-NRCS soil survey data. The GIS-based screening evaluates soil texture, soil permeability, and soil depth to characterize the suitability of each soil map unit. Other site selection factors include topography, surface hydrology, depth to groundwater, and current land use. Site characterizations occur at locations that appear well suited for managed irrigation.

Step 5: Site Characterization

To further assess the suitability of potential irrigation sites, an on-site evaluation determines specific site characteristics, including soil chemical and physical conditions, vegetation, hydrology, topography, and current land use.

The number and spatial distribution of soil profile description pits is approximately equal to the requirements for an Order 1 soil survey (Soil Survey Staff, 2007). Soil pits are excavated with a backhoe to a depth of at least 150 cm. Certified soil scientists describe each soil pit according to standard USDA-NRCS protocols (Soil Survey Division Staff, 2002). Soil samples are collected from each genetic horizon and analyzed by a certified commercial laboratory for pH, EC, SAR, saturation percentage, exchangeable Na percentage (ESP), percent lime, percent organic matter (%OM, surface horizon only), and soil texture. If the candidate site is selected for managed irrigation, the soil data collected during the feasibility assessment is used to establish baseline soil conditions, design the irrigation system, and to satisfy U.S. Bureau of Land Management (BLM) requirements for CNBG produced water management.

Step 6: Agronomic Planning and Design

Landowner preferences, soil type, and the projected root zone salinity resulting from the CBNG produced water in equilibrium with the soil amendments drives crop selection. Alfalfa and native forage grass mixes are the most common crops grown on managed irrigation sites within the PRB.

Center pivot sprinkler systems are preferred due to significant advantages in automation, overall control, runoff control, uniform water distribution, and decreased operation costs despite initial capital costs. The selection of a particular irrigation system is based on topography, soil conditions, land-owner preferences, size of the site, crop type, post-irrigation land use, and project economics.

Step 7: Soil Water Budget and Irrigation Scheduling

A spreadsheet-based soil-water budget determines the amount and timing of irrigation required to produce a healthy forage crop and ensure that adequate agronomic leaching occurs. A soil-water budget quantifies all water inputs to the soil and outputs from the soil through the following equation modified from the NRCS (2001):

$$Fg = ET + LF + SDL - Ppt - \Delta SW \qquad \textbf{(6)}$$

where:

Fg = gross irrigation water applied (cm)

ET = crop evapotranspiration (cm)

LF = agronomic leaching fraction (cm)

SDL = spray, drift losses, and canopy intercept evaporation from sprinkler systems, losses are estimated from irrigation efficiency values and expressed as a depth (cm)

Ppt = precipitation (cm)

ΔSW = change in soil-water content within the crop rooting zone.

The soil-water budget accounts for the losses due to spray, drift, and canopy interception by reducing by the efficiency of the irrigation system (i.e., irrigation efficiency). Irrigation efficiencies range between 70 and 90 percent. Evapotranspiration and precipitation gauges collect data on site, and water applications are adjusted based on the measurements. Soil water content is estimated using the methods presented by Saxton et al (1986).

Percolation through the root zone is required to move applied salts through the crop root zone. The soil water budget includes agronomic leaching requirements to prevent the soil salinity from exceeding the salinity of the produced water in equilibrium with the soil amendments. The agronomic leaching requirement (Ayers and Westcot, 1985) is calculated as follows:

$$LR = \frac{EC_w}{\left(\left(5 \times EC_e\right) - EC_w\right)} \qquad \textbf{(7)}$$

Where:

LR = Agronomic leaching requirement,

ECw = electrical conductivity of irrigation water (dS/m), and

ECe = average root zone soil electrical conductivity tolerated by the crop as measured on a soil saturated paste extract

Historical precipitation and ET data from the nearest weather station, along with the salinity tolerance of the selected crops, assist with the generation of preliminary monthly irrigation schedules. Crop growth, precipitation, and evapotranspiration measured at the site determine actual water application rates. Furthermore, it is assumed that no more than 20 cm per ha of CBNG produced water could be applied to a single field in any one month due to operational issues (i.e. amendment spreading, and harvesting) that prevent irrigation.

Step 8: Water, Soil, Crop, and Meteorological Monitoring

The purpose of monitoring CBNG managed irrigation sites is to maintain soil physical and chemical conditions at levels supportive of plant growth, ensure successful forage crop production, and incorporate monitoring data into management practices. The data collected from water, soil, crop, and meteorological monitoring is used to evaluate the performance of the managed irrigation site and determine if management strategies should be modified. Table 2 describes the monitoring plan employed at the managed irrigation sites. At each irrigation site, soil sampling transects are permanently established with handheld GPS units, prior to irrigation

Table 2. Managed irrigation monitoring plan.

Media	Frequency	Location	Method	Parameters*†
Soil chemistry	Spring - prior to the irrigation season	defined transects	Composite soil samples collected from: 0 to 15 and15 to 30 cm.	pH, EC, SAR, ESP, Ca, Na, Mg, % Lime, SO_4^{2-}, and $HC0_3^-$. %OM will be analyzed in the 0 to 15 cm depths. N,P,K,Zn as required.
	Fall - after the irrigation season	defined transects	Composite soils samples from: 0 to15, 15 to 30, 30 to 60, 60 to 90, 90 to150, and 150 to 240 cm with a Giddings soil probe.	pH, EC, SAR, ESP, Ca, Na, Mg, % Lime, SO_4^{2-}, and $HC0_3^-$. %OM will be analyzed in the 0 to 15 cm depths. N,P,K,Zn as required.
Soil Infiltration	Baseline and annually thereafter	Defined monitoring locations	Tension infiltrometer	Soil infiltration rates
Soil Structure	Spring and fall	defined transects	Visual to a depth of 60 cm	Soil structure and tilth
Water Quality	Annually- beginning of irrigation season	Irrigation water intake	Grab sample	pH, EC, major ions
Water Quantity	Weekly- during the irrigation season.	Each pivot	Meter reading	Meter reading
Crop Monitoring	Monthly- during the irrigation season.	Along a defined transect	Visual	Germination, emergence, vigor, and weed infestations
	After each harvest	Each crop type	grab samples of bale cores	SO_4^{2-}, NO_3^-, Ca, Mg, Na, crude protein, and percent moisture
Climate	Weekly- during the irrigation season.	ETGage, rain gauge or from nearest meteorological monitoring station	Visual	Evapotranspiration, precipitation, and temperature

Note:

* Abbreviations are defined as follows: SAR = sodium adsorption ratio, EC = electrical conductivity of soil saturated paste extract, %OM= percent organic ESP = exchangeable sodium percentage.

† All chemical analyses are completed by certified commericial laboratories.

with CBNG produced water. Soil monitoring occurs at least twice annually, prior to and following the irrigation season. Samples are collected from the 0 to 15 cm and 15 to 30 cm depth increments during the spring sampling event, and summer sampling event if applicable, with a bucket auger. During fall sample collection, following the irrigation season, a truck-mounted Giddings probe (Giddings Machine Company, Windsor, CO) is used to collect samples from the following depths: 0 to 15 cm, 15 to 30 cm, 30 to 60 cm, 60 to 90 cm, 90 to 150 cm, and 150 to 240 cm. Within an irrigation area, soil samples are composited by depth to create a single sample for each depth interval. Baseline soil infiltration measurements were made with a tension infiltrometer (Soil Measurement Systems, Tucson, AZ). Soil infiltration measurements occur at three locations within the irrigation area and at three locations outside the irrigation area, which serve as a non-irrigated reference. Each location includes three replicates

Step 9: Irrigation and Crop Management Plans

Annual irrigation and crop management plans serve to address landowner and land use goals, crop selection, site preparation, seeding, irrigation system operations, harvesting and or grazing plans, soil amendment application rates and scheduling, irrigation scheduling, leaching requirements, and monitoring. Annual updates to irrigation and crop monitoring plans ensure active and responsive management.

Step 10: Site Closure Planning

Site closure planning is a critical component of managed irrigation operations. Prior to site closure, soil chemical and physical conditions are evaluated relative to post-irrigation land use goals, pre-irrigation conditions, and landowner preferences. If necessary, a final amendment application occurs to prevent the formation of sodic soil conditions. A post-closure monitoring plan based on site-specific objectives ensures that soil physical and chemical conditions at the site are supportive of post-closure land use goals.

Managed Irrigation Projects

The ten-step process described above governs the operation of the six managed irrigation sites in the PRB selected for this study. Two of the irrigation areas, referred to as PR Pivot 1 and Pivot 2, are near the Powder River. Two of the irrigation areas are near the Tongue River and named TR Pivot 1 and TR Pivot 2. The last two irrigation areas, PC Pivot 1 and PC Pivot 2, are near Pumpkin Creek. Table 3 summarizes the site characteristics. Table 4 presents the long-term water quality for each managed irrigation area.

Table 3. Site characteristics for case study locations

Location	Size ha	Years Irrigated	Soil Texture	Crop
TR Pivot 1	20	5	Sandy Clay Loam	Alfalfa
TR Pivot 2	20	5	Loam/Sandy Loam	Alfalfa
PR Pivot 1	5	3	Sandy Clay Loam	Native Range Grasses
PR Pivot 2	16	3	Sandy Clay Loam	Native Range Grasses
PC Pivot 1	15	4	Clay Loam	Native Range Grasses
PC Pivot 2	10	4	Clay Loam	Native Range Grasses

Results

Long-term Produced Water Quality

The minimum and maximum values, presented in Table 4, indicate that produced water quality varies considerably through time. This variation highlights the need for active and responsive management. The average pH of the produced water is similar for all of the irrigation areas (Table 4). At each of the irrigation areas, the salinity of the produced water has been suitable for moderately tolerant species (Maas, 1990) throughout the duration of study (Table 4). The EC is considerably higher at the Powder River and Pumpkin Creek irrigation areas (Table 4). However, the SAR tends to be the highest at the Tongue River irrigation area (Table 4). When evaluated based on the work of Ayers and Westcott (1985, Fig. 21) the application of untreated produced water may create a moderate to severe reduction in infiltration rate. Thus, agronomic leaching and soil conditioning is essential to assure that soil infiltration rates remain stable. The boron concentrations reported at the Tongue River Area are very low and support the findings of Rice et al. (2000).

Table 4. Average CBNG Produced water quality for the study areas in Powder River Basin..

Location		pH	EC	SAR	B	Anions			Cations		
		pH	EC	SAR	B	HCO_3	CO_3	SO_4	Ca	Mg	Na
		s.u.	dS m^{-1}		mg L^{-1}	mg L^{-1}	mg L^{-1}	mg L^{-1}	mg L^{-1}	mg L^{-1}	mg L^{-1}
Tongue River Area	minimum	7.2	1.4	22	0.07	970	0	1.0	4.8	2.3	380
	maximum	8.9	3.1	60	0.20	1700	1300	430	18	7.7	700
	average*	8.1	2.3	43	0.13	1300	590	130	9.3	4.0	570
Powder River Area	minimum	7.6	3.3	12	—	2300	—	11	12	19	600
	maximum	8.8	4.1	36	—	3000	—	27	90	72	1000
	average†	8.2	3.5	30	—	2500	—	19	31	32	880
Pumpkin Creek Area	minimum	7.2	2.8	21	—	2600	35	0	6.0	17	760
	maximum	9.0	4.1	38	—	3100	200	65	45	69	1090
	average‡	8.1	3.7	30	—	2900	120	14	27	33	940

Note: Samples were obtained using standard methods and analyzed by a certified commericial laboratory.

* The values reported are an average of ten values (n= 10); except for B which is an average of three values (n= 3).

† The values reported are an average of seven values (n= 7).

‡ The values reported are an average of eight values (n= 8).

Soil Chemical Conditions

Three primary factors influence soil EC at managed irrigation areas;- CBNG irrigation, precipitation and amendment application (Fig. 2). Soil EC has increased through time, as anticipated, in the 0 to 15 cm and 15 to 30 cm depths at each of the irrigation areas (Fig. 2). Although soil EC has increased, the salinity level is still suitable for the forage crops grown at each location. Both CBNG irrigation and amendment application result in an increase of soil EC. Amendment application increases soil EC rather quickly (Fig. 2), where as CBNG irrigation appears to influence soil EC less immediately. Electrical conductivity at the soil surface (0 to 15 cm) tends to be more variable than soil EC in the subsurface (15 to 30 cm). The soil surface EC is generally lower in the spring and early summer due to additional precipitation and snowmelt. This trend results in conditions more favorable for seed germination.

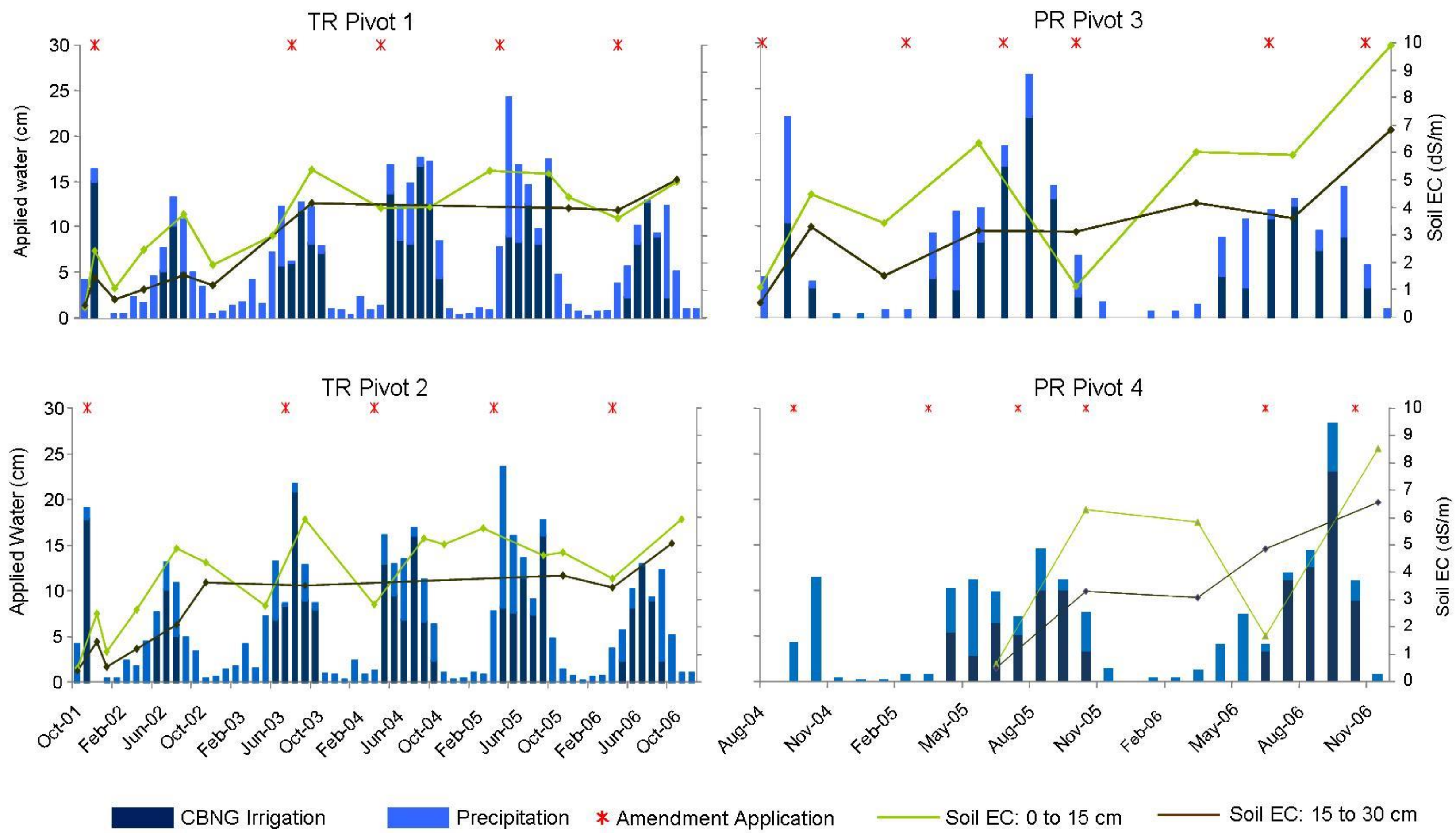


Figure 2. Soil electrical conductivity as influenced by CBNG irrigation, precipitation and amendments

Soil Infiltration Rates

An infiltration study completed at TR Pivots 1 and 2, following three years of managed irrigation with CBNG water, measured infiltration at 15 locations in the pivot areas and at 15 locations in adjacent non-irrigated reference areas. Infiltration rates in each of the pivots are typical for the soil type. The infiltration rates measured in TR Pivot 1 are not significantly different from the non-irrigated reference (Table 5, n=15, p=0.05). The infiltration rates measured in TR Pivot 2 are significantly different from rates measured in the non-irrigated reference (Table 5, n=15, p=0.05). The difference is due to both physical and chemical changes incurred during irrigation. Physical changes likely result from the physical effects of irrigation, compaction from amendment application, tillage and other agronomic activities (Hillel, 1998).

Table 5. Soil infiltration rates in Tongue River Pivots 1 and 2 and respective non-irrigated reference areas.

	Infiltration rate (cm/hr)			
	TR Pivot 1	TR Pivot 1 Reference	TR Pivot 2	TR Pivot 2 Reference
	0.84	2.34	2.41	1.60
	4.04	1.91	0.91	2.82
	2.46	8.26	1.88	1.19
	1.52	6.30	2.36	4.19
	1.24	3.25	1.93	5.03
	3.61	3.48	2.11	3.02
	3.63	0.84	2.41	0.64
	3.02	0.51	1.80	2.49
	2.46	2.46	2.11	9.14
	1.42	0.23	2.11	0.56
	2.11	1.42	1.07	6.27
	3.15	0.91	1.73	12.19
	4.04	1.14	1.02	9.22
	1.80	1.07	1.96	5.18
	1.27	1.70	2.59	10.41
Minimum	0.84	0.23	0.91	0.56
Maximum	4.04	8.26	2.59	12.19
Average	2.44	2.39	1.89	4.93
Standard Deviation	1.09	2.23	0.52	3.76

Soil Profile Characteristics

After six years of managed irrigation with CBNG produced water, the soil profiles at PC Pivot 1 and PC Pivot 2 were compared to non-irrigated reference profiles (Fig. 3). Soil crusting and dispersion are not present in the irrigated areas. Soil structure in the irrigated areas remains similar to soil structure in non-irrigated areas (Fig. 3).

Summary and Conclusions

Seven years of full-scale irrigation experience with CBNG produced water in the PRB suggests that active and responsive management maintains soil physical and chemical conditions at targeted levels that are supportive of plant growth. Soil EC and SAR increase, as anticipated, due to both CBNG produced water and amendment applications. However, management practices maintain soil structure and hydraulic function for the life of the project.

Managed irrigation is a practical and mutually beneficial water management strategy. Within the PRB, appropriately selected and managed sites have improved range conditions, through establishment of a vigorous stand of desirable forage species and increased yields during a period of on-going drought. With careful implementation, managed irrigation can maintain soil chemical and physical conditions that are supportive of plant growth. The techniques used for managed irrigation with CBNG produced water may prove useful in other situations where low quality waters are available for irrigation.

Acknowledgements

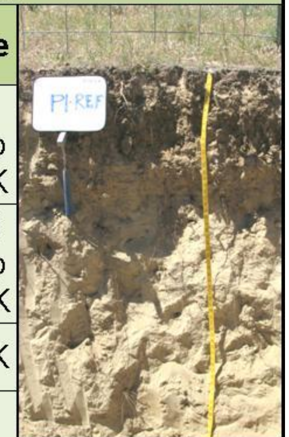
The authors would like to thank Fidelity Production & Exploration Company and Williams Production RMT Company

PR Pivot 1

Horizon	Depth (in)	Texture	Structure
Ap	0-3	Loam	2, M, SBK
Bt	3-9	Clay Loam	2, M, SBK
Bk	9-23	Clay Loam	2, M, SBK
Ck	23-33	Clay Loam	MA
C	33-60+	Sandy Clay Loam	MA

PR Pivot 1 Reference

Horizon	Depth (in)	Texture	Structure
Ap	0-3	Clay Loam	2, F, PL parting to 2, F, SBK
Bt	3-13	Clay Loam	1, M, PR parting to 2, M, SBK
Bk	13-25	Sandy Loam	1, C, SBK
C	25-60+	Sandy Loam	MA



PR Pivot 2

Horizon	Depth (in)	Texture	Structure
Ap	0-5	Loam	2, M, GR
Bt	5-13	Clay Loam	2, M, PR, parting to 2, M, SBK
Bk	13-27	Clay Loam	2, C, SBK
Ck	27-57	Clay Loam	MA
C	57-60	Clay Loam	MA

PR Pivot 2 Reference

Horizon	Depth (in)	Texture	Structure
A	0-4	Loam	1, M, GR
Bt	4-11	Loam	2, M, SBK
Bw	11-37	Loam	2, C, SBK
C	37-60	Sandy Loam	MA

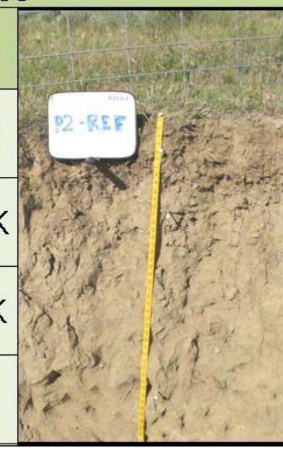


Figure 3. Soil profile descriptions for Powder River Pivots 1 and 2 and corresponding non-irrigated reference area

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