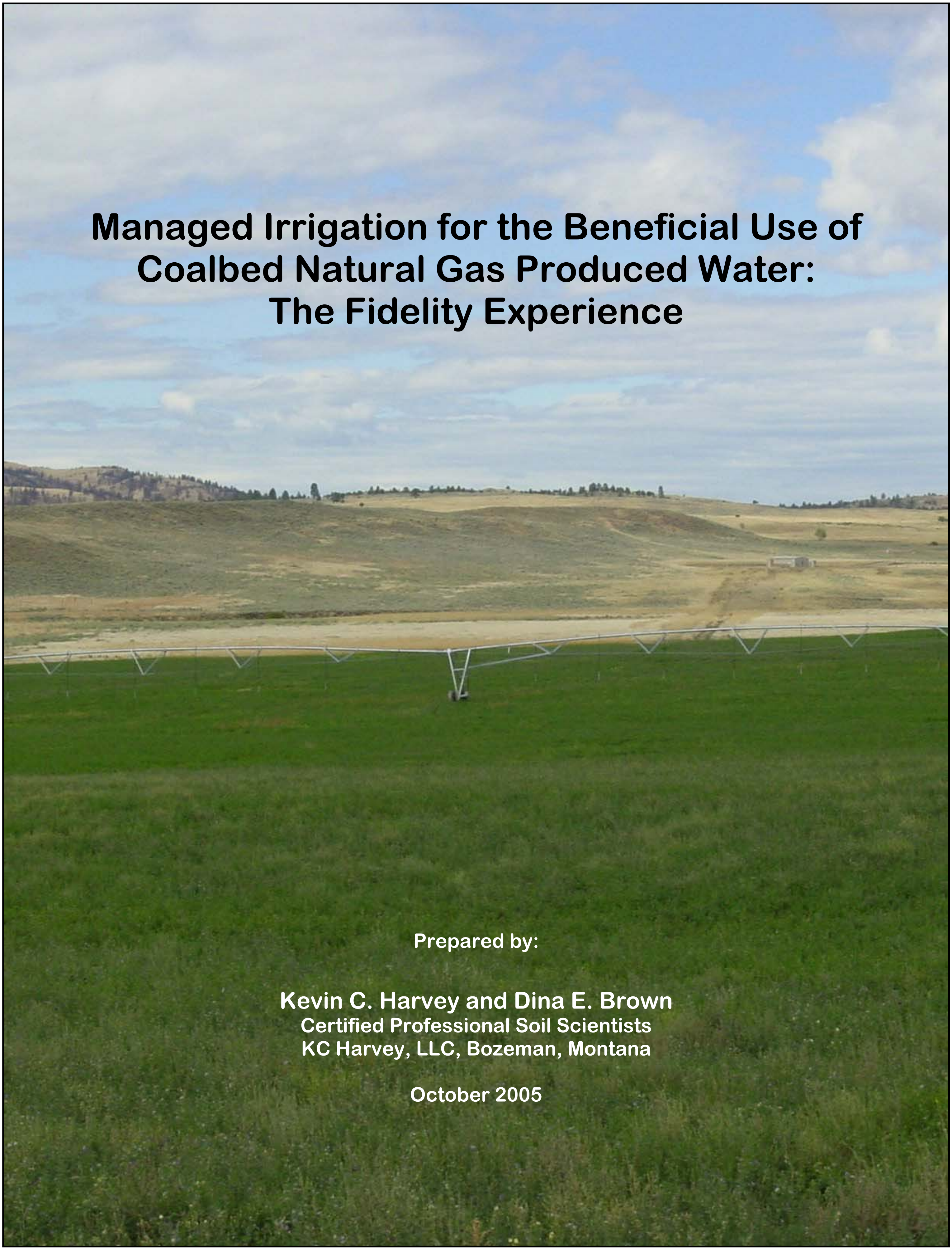

Managed Irrigation for the Beneficial Use of Coalbed Natural Gas Produced Water: The Fidelity Experience

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October 2005

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Introduction

The methods for managing and using groundwater produced by coalbed natural gas (CBNG) operations have become an important issue that is being debated by the public, Federal and State agencies, special interest groups, and energy companies. The purpose of this publication is to provide information about using produced water in a beneficial manner to produce forage for livestock and wildlife in the Powder River Basin of southeastern Montana and northeastern Wyoming. The information, data, and processes described in this publication are based on the research and development, and the full-scale managed irrigation operations performed on behalf of and by Fidelity Exploration & Production Company (Fidelity) of Sheridan, Wyoming.

What is Managed Irrigation?

Managed irrigation with unaltered groundwater produced during CBNG operations is defined as: *the application of soil science, water chemistry, agricultural engineering and agronomic principles to utilize CBNG-produced water in a beneficial manner to produce forage for livestock and wildlife while protecting soil physical and chemical properties*. Managed irrigation practices include:

- selection of appropriate irrigation sites with suitable topography, soils, and hydrology;
- close cooperation with the landowner to ensure that the beneficial objectives of irrigation and the production of a crop are achieved;
- water balance analyses to support irrigation system sizing and design;
- water treatment or soil amendments to mitigate the potential affects associated with the sodium bicarbonate chemistry of produced water;
- irrigation scheduling and maintenance of a suitable leaching fraction to prevent the accumulation of salts in the root zone;

- selection and maintenance of a suitable crop that is tolerant of expected soil moisture and salinity levels;
- prevention and control of irrigation water runoff;

- periodic monitoring of water, soil, and vegetation during the life of the project; and
- site closure planning and implementation in accordance with landowner objectives.

Managed irrigation is one alternative out of several available for managing CBNG-produced water. Its suitability as a water management alternative depends on many factors, including produced water chemistry, site and soil characteristics, landowner objectives, and project economics. As such, its suitability can only be evaluated on a project- and site-specific basis.

How is Managed Irrigation Different from Land Application Disposal?

A common misconception in the Powder River Basin is that managed irrigation and land application disposal or “LAD,” are different names for the same process. Managed irrigation is substantially different from land application disposal in several ways. Managed irrigation, as defined above, is designed, located, and operated in an agronomic manner to grow a forage crop, protect soil physical and chemical conditions, and to minimize any potential environmental impacts. In contrast, land application disposal operations apply wastewater to the surface with the goal of simply disposing of and/or treating wastewater within the soil-plant system. Additionally, land application disposal typically relies on the maximum soil infiltration rate to maximize the discharge and treatment of wastewater. Whereas, managed irrigation application rates are based on the evapotranspiration requirements of the crop and the prescribed agronomic leaching requirement.

Where Does the Water Come From?

The water that is generated during the production of CBNG in the Powder River Basin is commonly referred to as “produced water.” CBNG-produced water is naturally occurring groundwater. If present, the natural gas can be recovered from wells when groundwater contained in the coal seams is pumped to the surface to reduce pressure. The CBNG production process does not change the chemical nature of the water within the coalbed aquifer. All groundwater contains a mixture of naturally occurring chemicals. The chemicals dissolved in coalbed water result from natural processes that occur as rainfall and snowmelt percolate through the soils and deeper geologic formations during recharge of the groundwater system. These natural processes result in groundwater that is rich in sodium and bicarbonate minerals.

Why is the Water a Concern?

CBNG-produced water is often of higher quality than other available water sources in the Powder River Basin of Montana and Wyoming. Groundwater from coal seams is commonly used for domestic purposes, including drinking. Because of its low to moderate level of salinity, it is a very good source of water for livestock and wildlife use. However, because of the naturally elevated levels of sodium and bicarbonate ions dissolved in the water, irrigating with this water, if not properly managed, could be problematic.

The suitability of water used for irrigation depends on a number of factors including the type of crops grown, the soil type, irrigation methods, and the types and quantity of salts dissolved in the water. Water quality guidelines for assessing irrigation water suitability generally consist of four components; salinity, sodicity, alkalinity, and specific ion toxicity. The most comprehensive and widely used guidelines were formulated for the Food and Agriculture Organization (FAO) of the United Nations by Ayers and Westcot (1985) and the University of California by Hansen and others (1999).

Salinity

All irrigation waters contain a mixture of naturally occurring dissolved salts. Soils irrigated with water will contain a similar mix of salts, but the concentration of salts in the irrigated soils is usually higher than in the applied water. Salts can be defined as minerals that dissolve in water, e.g., table salt, which is sodium chloride. Typical salt constituents in water and soil include calcium, magnesium, sodium, potassium, sulfate, chloride, carbonate, and bicarbonate. The concentration of salts in water is measured two ways -- total dissolved solids (TDS) or electrical conductivity (EC). TDS, measured in milligrams per liter (mg/L) is a laboratory method to measure the dissolved salts present in a sample. EC, measured in deci-Siemens per meter (dS/m), is a field or laboratory method that provides a reliable and widely used index of salinity. As the dissolved salt content of a sample increases, its ability to conduct electricity also increases, which can be readily measured. EC is the most commonly used measure of water and soil salinity because it is a rapid and inexpensive test.

The salinity of irrigation water does not directly effect soil physical properties. Instead, the presence of increased salts hinder the plant’s ability to extract water from the soil and are a concern if the salt level is high enough to affect crop yield. Plant species vary with respect to salt tolerance. Generally, most forage and field crops grown in southeastern Montana and northeastern Wyoming are moderately to strongly salt tolerant. For example, based on research conducted by the USDA Natural Resource Conservation Service (NRCS) at the Bridger Plant Materials Center in Bridger, Montana, the soil salinity threshold where alfalfa begins to exhibit yield declines is 4.0 dS/m (Bridger Plant Materials Center, 1996). With careful management and suitable crops, water with EC ranging from 4.0 to 7.5 dS/m has been used successfully for irrigation (Rhoades et al., 1992). CBNG water from the Powder River Basin has an average salinity of around 2.0 dS/m, which is suitable for irrigation.

Sodicity

For CBNG-produced water, the key issue with respect to irrigation suitability is the naturally occurring sodium levels and its potential affect on soil infiltration and permeability. The infiltration and permeability of clayey soils can decrease if an abundance of sodium ions are adsorbed by the clay minerals in soil. Excessive adsorbed or exchangeable sodium can occur in clayey soils as a result of sustained use of irrigation water that is relatively high in sodium and relatively low in calcium and magnesium. Consequently, the ratio of sodium to calcium and magnesium ions in irrigation water is an important property affecting the infiltration and permeability of a soil. The index used to measure the hazard related to sodium abundance or sodicity is the sodium adsorption ratio or SAR.

The SAR can be calculated from the sodium, calcium, and magnesium concentrations using the formula:

$$SAR = [Na^{+}] \div \sqrt{\frac{[Ca^{++}] + [Mg^{++}]}{2}}$$

where the chemical concentrations are in milliequivelents per liter (meq/L).

Clay minerals in soils are negatively charged and consequently attract ions with a positive charge such as sodium, calcium and magnesium. When sodium comprises more than about 15% of the exchangeable ions in the soil, the clay minerals can begin to repel one another causing the soil structure to degrade (i.e., swell and disperse). The swelling of clay minerals and continued dispersion, and subsequent degradation of soil structure, can reduce the rate of water infiltrating the soil and the permeability of water through the soil. In general, soils with moderately high, to high, clay contents are at higher risk.

What is not apparent from the SAR formula is the fact that the higher the salinity of the water, the higher the SAR can be without impacting soil structure and impairing soil infiltration and permeability. Put another way, for a given SAR, infiltration rates generally increase as salinity (measured by the EC) increases. The changes in soil infiltration and permeability occur at varying SAR levels. Ayers and Westcot (1985) and Hansen et al. (1999) describe the relationship between salinity and sodicity in irrigation water and the potential effects on soil infiltration and permeability.

Most CBNG-produced waters in the Powder River Basin of Montana and Wyoming have relatively high SAR values making them potentially unsuitable for irrigation on most soils. Therefore, to beneficially use this water for forage production, some type of water treatment (e.g., sodium removal) or soil/water conditioning (e.g., calcium addition) may be required to mitigate the effects of the elevated SAR.

Alkalinity

Alkalinity is a measure of the buffer capacity of water or the ability to neutralize an acid. The major form of alkalinity in CBNG-produced water is bicarbonate. Bicarbonate present in irrigation water will react with the available calcium and magnesium and form insoluble calcium carbonate (lime) or magnesium carbonate precipitates. As indicated in the SAR formula above, a reduction of available calcium and magnesium raises the effective SAR of the water. Bicarbonate concentrations in CBNG-produced water from the Powder River Basin typically range from 750 mg/L to 3,000 mg/L. These relatively high values for irrigation water can cause pH increases in water and soil, and subsequent increases in water and soil SAR. To prevent the reduction in available (or added) calcium, the bicarbonate alkalinity must be neutralized with an acidifying agent (for example, sulfur soil amendments, which oxidize to produce sulfuric acid).

Specific Ion Toxicity

While generally not a concern with respect to CBNG water in the Powder River Basin, sodium, chloride, and boron ions can be toxic to certain crops if their concentrations are too high in irrigation water. Damage from sodium and chloride toxicity usually occurs only in woody plants such as tree and vine crops where soil salinity is extremely high or when saline water is used for sprinkler irrigation. Chloride concentrations in CBNG-produced water from the Powder River Basin are typically very low. Since tree and vine crop types are not usually grown on managed irrigation sites, or by local farmers and ranchers in the Powder River Basin, sodium and chloride toxicity is not an issue. Boron concentrations in produced water are typically below detectable levels to very low levels and should not be a potential toxicity problem.

How Did Fidelity Develop Managed Irrigation?

Background

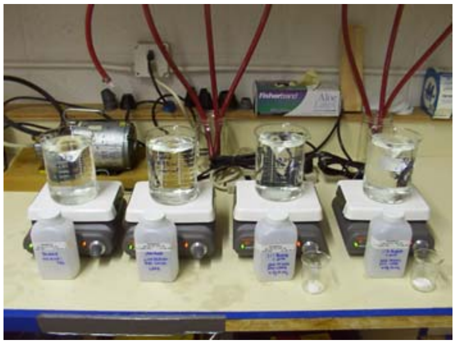
In 2000, early in the development of CBNG production in Montana and Wyoming, Fidelity recognized that a larger volume of produced water might be generated than could be discharged through the National Pollutant Discharge Elimination System process. Fidelity began seeking options for managing the produced water, including beneficial uses of the unaltered groundwater. One such possibility was using the produced water to irrigate a forage crop that local ranchers could use in their cattle operations.

However, irrigation with CBNG-produced water had never been done. Could the produced water be safely used for irrigation? As discussed above, sodium in irrigation water can be a hazard to soils because it causes clay particles in soil to disperse and form a hard surface crust. This crust can then become a barrier to water movement and plant growth. If, however, enough calcium is present in the soil, the clay particles will stay aggregated. Therefore, adding calcium to the soil-water system will negate the impacts of the sodium. Water or soil with relatively more sodium than calcium has a high SAR and is considered sodic. Often CBNG-produced water is referred to as saline, or having a high salt content. But in reality it is the sodicity, not the salinity that is the primary concern. Salinity levels in CBNG-produced waters are actually quite moderate.

In addition to relatively high SAR levels, the CBNG water is naturally enriched with bicarbonate alkalinity. In alkaline waters such as the CBNG groundwater, any added calcium will react with the bicarbonate and drop out of solution as lime, or calcium carbonate. The calcium in calcium carbonate then becomes unavailable to keep the clay particles in the soil aggregated. So, to irrigate with CBNG-produced water, the bicarbonate needs to be neutralized with an acid so that calcium can be added to negate the effects of the sodium. The practice of neutralizing bicarbonate alkalinity and adding calcium is based on established soil and water chemistry principles, and decades of farming experience.

Modeling and Initial Laboratory Testing

To test the possibility of irrigating with the CBNG-produced water from its Wyoming production areas, Fidelity embarked on a long series of scientific tests that were performed by soil science and water chemistry experts. First, geochemical equilibrium models were developed for CBNG-produced water. The modeling results indicated that by using standard agricultural amendments such as elemental sulfur and gypsum, the produced water could be used for irrigation. Sulfur reacts in the soil with oxygen and water to produce sulfuric acid, which in turn neutralizes the bicarbonate alkalinity. The gypsum (calcium sulfate dihydrate) dissolves to yield soluble calcium to lower the SAR and reduce the risk to soil structure. This process is discussed in more detail below.



The modeling results were then validated in the laboratory using “jar tests.” The jar tests involved blending differing ratios of produced water with appropriate amounts of an acidifying agent (sulfuric acid) and sources of calcium (e.g., gypsum and calcium chloride). Results of the modeling and jar tests indicated that the ability existed to “condition” the CBNG-produced water for irrigation.

Results of Bench-Scale Testing

The promising results from the modeling and jar tests led to a “bench-scale” laboratory test using actual columns of soil and CBNG-produced water from the Tongue River drainage in the Powder River Basin. The soil was collected from a candidate irrigation area within Fidelity’s Wyoming production area. The produced water was collected from a CBNG well in the same area and exhibited an EC of 2.5 dS/m and an SAR of 60.

To start the test, 18-inch long, undisturbed columns of soil, were collected in eight-inch diameter plastic pipes, and brought into the laboratory. In the bench-scale laboratory test, three treatment approaches were tested: (1) amendments applied directly to the soil; (2) amendments added to the produced water; and, (3) blending the produced water with irrigation water from a local water source. Soil and water amendment rates were based on the chemistry of the water and the results of geochemical equilibrium modeling. The amendment rates were designed to reduce the SAR of the soil-water system to approximately 8. Experimental controls, consisting of: (1) produced water with no treatment; and (2) water from the Tongue River were also included in the testing. The soil columns were irrigated for 84 days to simulate several years of irrigation in the field.

To determine the effects of the treatments, soil samples from the columns were measured for pH, EC, and SAR. Results from four of the treatments and from a control column that was not irrigated or treated are shown in Table 1. At the conclusion of the test, average soil pH values were within the typical range for most undisturbed range soils of 6.5 to 8.4. As expected, soil EC increased in all treatments when compared to baseline conditions. Also as expected, the largest increase in soil EC was seen in the soil applied amendment treatment. However, soil samples from all treatments exhibited average EC values of less than 4 dS/m, below the 4 to 12 dS/m range of soil salinity thresholds for western rangeland and forage plant species (Bridger Plant Materials Center, 1996).

Table 1
Results of soil sampling and analysis from the Fidelity laboratory bench-scale tests.

Treatments	Average pH	Average Electrical Conductivity (dS/m)	Average Sodium Adsorption Ratio
Gypsum and sulfur applied to the soil; CBNG-produced water applied to the soil	7.8	2.9	7.5
Gypsum and sulfuric acid added to the CBNG-produced water; CBNG-produced water applied to the soil	7.5	2.8	8.9
Untreated CBNG-produced water applied to the soil	8.3	1.6	20
Untreated Tongue River water applied to the soil	7.7	0.69	0.69
Non-irrigated control (no water or treatments were applied to the soil)	7.9	0.41	0.44

Except for the produced water control treatment, the soil SAR values for each treatment were well below the established sodic soil threshold value of 13 (Brady, 1990) and the management target of 10. As anticipated, irrigation of the soil column with CBNG-produced water (with no soil amendments) resulted in an average soil SAR of 20. The soil within this column was clearly dispersed, reducing infiltration and permeability to near zero. In contrast, irrigation with CBNG-produced water on soil, amended with elemental sulfur and gypsum resulted in an average soil SAR of 7.5. Effects on soil structure and permeability of the soil column amended with calculated amounts of sulfur and gypsum were not apparent. The laboratory column test demonstrated the feasibility of using the agricultural soil amendments, elemental sulfur and gypsum, in combination with the CBNG-produced water to safely irrigate the soils.

Results of Full-Scale Testing

The successful bench-scale test led to a full-scale, 100-acre pilot test, where sulfur and gypsum amendments were applied to the soil and produced water was applied using center-pivot irrigation equipment. The post-irrigation soil samples exhibited little change in pH compared to the pre-irrigation samples. As expected, the average surface soil EC levels in the amended soils increased following irrigation, from 0.38 to 2.4 dS/m. The purpose of gypsum amendments was to add calcium to the soil system to balance the effect of sodium added by the produced water. Following irrigation, the average dissolved calcium concentration increased substantially. SAR values in the amended soils increased only slightly after irrigation, consistent with the 6.5 inches of water that was applied. The full-scale test successfully demonstrated that the elemental sulfur effectively controlled the bicarbonate in the produced water and allowed the added calcium in the gypsum to counter-balance the sodium introduced in the produced water.

Results of Long-Term Operations

Since the successful full-scale pilot test, Fidelity has embraced managed irrigation as one of its preferred methods for managing CBNG-produced water and irrigates over 850 acres in its Tongue River project area of Wyoming. With careful addition of elemental sulfur and gypsum amendments to the soil surface, irrigation with CBNG-produced water is producing up to 4 tons per acre of alfalfa annually for local ranchers. This has been done during a period of severe drought.

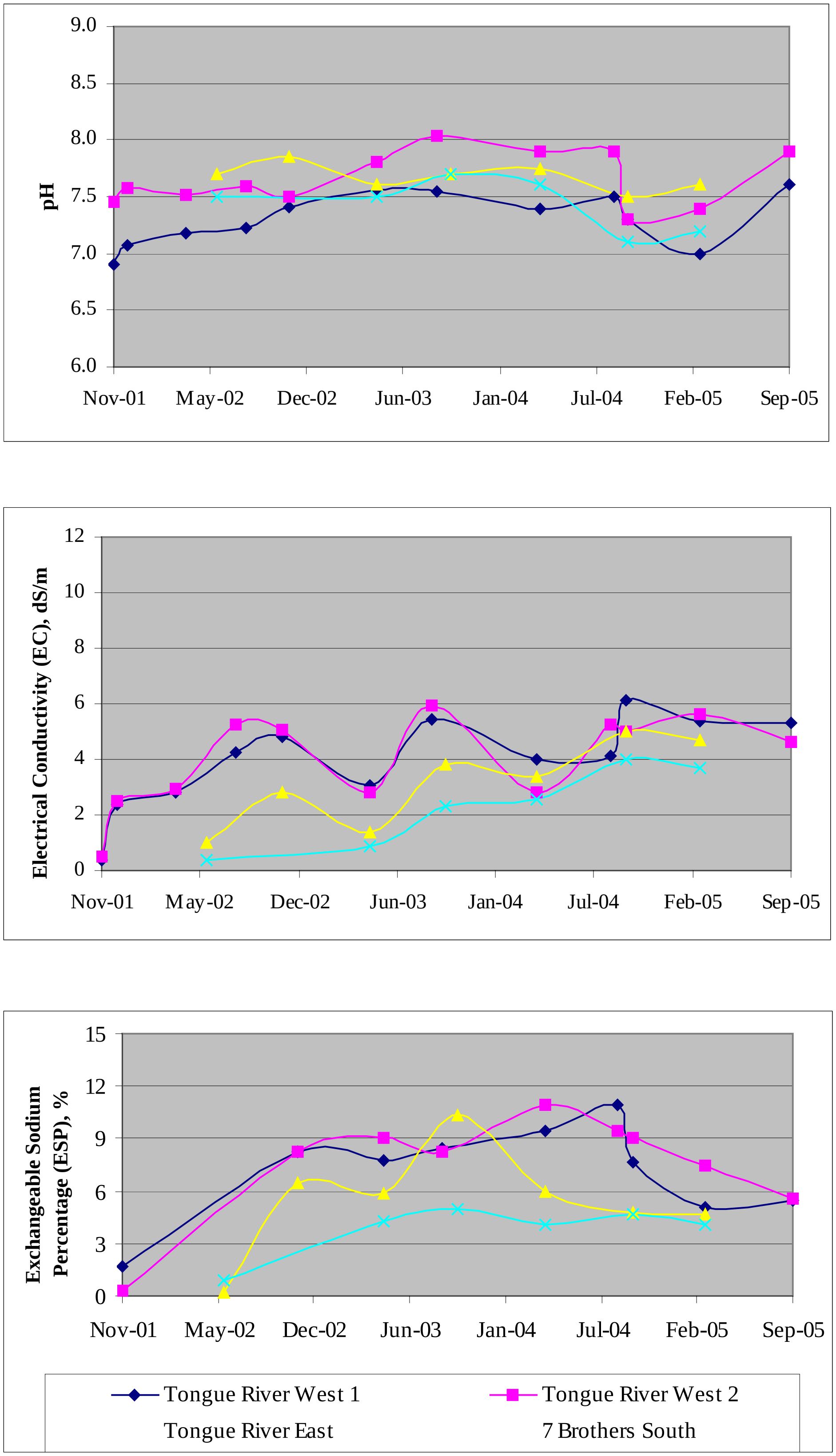
To protect the soil resource, Fidelity employs an intensive soil-monitoring program. The monitoring program includes, among other things, soil sampling at the beginning and end of every irrigation season to track the soil chemical and physical condition. Soil sampling results from four of Fidelity's managed irrigation areas that have been irrigated as long as four years are shown in Figure 1. Each of the four project areas shown in Figure 1 is irrigated using center pivot irrigation equipment and each receives between 20 and 25 inches of CBNG-produced water annually. The EC of the produced water used to irrigate the areas generally ranges between less than 2 and 2.5 dS/m, while the SAR ranges between about 20 and 60. All four areas support healthy stands of alfalfa.

To begin with, soil samples were collected from each irrigation area before managed irrigation operations were started to document "baseline" conditions. The samples were analyzed in a laboratory for pH, EC, SAR, and exchangeable sodium percentage (ESP), among other things (ESP is a more accurate laboratory method that measures the amount of sodium ions held on the soil exchange sites, while soil SAR was developed as a less expensive method to estimate ESP). Pre-irrigation soil pH levels generally ranged between 6 and 8.5. Pre-irrigation EC levels generally ranged between less than 1 and 5 dS/m, while the ESP usually ranged between less than 1 and 5 percent.

Over time soil pH levels in samples collected from Fidelity's four managed irrigation areas have generally remained between 7.0 and 8.0 and have not greatly changed from pre-irrigation values. Soil EC levels have increased over time in the samples collected from the managed irrigation areas and have generally stabilized between 4.0 and 6.0 dS/m, as predicted. Soil EC levels were expected to increase with the addition of "salts" from the sulfur and gypsum soil amendments and from the CBNG-produced water. As can be seen in the fluctuating EC levels in Figure 1, winter and spring precipitation result in a decrease in EC due to natural leaching of the salts down through the soil profile. ESP values are shown in Figure 1 and are used to monitor the sodicity of the soil, similar to soil SAR results. In the soil samples collected in the Fidelity managed irrigation areas, ESP values increased initially, at the start of operations, and then generally stabilized over time. This response was expected and indicates that the added calcium has reached equilibrium with the sodium being added by the produced water during irrigation. For reference, sodic soils are defined as having ESP levels greater than 15% (U.S. Salinity Laboratory Staff, 1954). All of the Fidelity managed irrigation areas have ESP levels that are well below 15%, and are generally below 10%.

Figure 1

Median pH, average electrical conductivity, and average exchangeable sodium percentage in surface soil (0 to 6 inches) samples from four Fidelity managed irrigation areas.



Managed irrigation with CBNG-produced water results in changes to the soil chemistry during operations, including fluctuating soil salinity levels that can increase up to approximately 6.0 dS/m, and an increase in soil ESP up to a maximum of about 10%. After completion of managed irrigation operations, an application of gypsum to the soil surface, followed by natural precipitation that will move the calcium in the gypsum down into the soil and leach residual salts, likely resulting in a final soil EC of less than 3 dS/m and an ESP of less than 5 percent.

How Does Fidelity Implement Managed Irrigation?

The research and development program discussed above, along with four years of full-scale operational experience, has led to the development of a process for evaluating, designing, operating, monitoring, and closing CBNG managed irrigation systems in an environmentally sound manner. This process has been successfully employed by the authors of this document and their clients on managed irrigation projects totaling over 2,000 acres in the Powder River Basin of Wyoming. The primary components of the managed irrigation process are as follows:

- Irrigation Water Quality Suitability Assessment
- Soil Amendment Prescriptions
- Project Water Balance Estimates
- Site Selection
- Site Characterization
- Crop Selection
- Selection and Design of Irrigation Systems
- Soil Water Balance Modeling and Irrigation Scheduling
- Water, Soil, Crop, and Meteorological Monitoring
- Development of Irrigation and Crop Management Plans
- Site Closure Planning

Each of these components is discussed below.

Irrigation Water Quality Suitability Assessment

As discussed above, to assess the suitability of produced water for irrigation, four specific areas are addressed: salinity, sodicity, alkalinity, and specific ion toxicity using the criteria specified in Ayers and Westcot (1985) and Hanson et al. (1999). This is the first step in any managed irrigation project to determine overall project feasibility. Soil and/or water conditioning prescriptions are then developed (if necessary) based on the chemistry of the irrigation water to allow long-term irrigation with CBNG-produced water.

Soil Amendment Prescriptions

The naturally occurring sodicity of CBNG-produced water, as measured by the SAR, is the primary concern to be addressed before this water can be used for irrigation and forage production. The SAR formula presented above indicates that two general treatment methods would result in a reduction in SAR prior to irrigation: (1) removal of sodium, or (2) addition of calcium and/or magnesium (the scientific literature suggests that calcium is more effective than magnesium in lowering the effect of sodium in soils, therefore, magnesium addition will not be discussed further). Salt removal water treatment systems (e.g., reverse osmosis, ion exchange, etc.) are technically feasible; however, due to operational and economic limitations and issues associated with concentrated reject waters, they are not usually used in conditioning water for managed irrigation projects. The process of calcium addition, however, is a common practice used today in the Powder River Basin.

The level of bicarbonate alkalinity limits the maximum amount of calcium that can be dissolved in produced water. The minimum SAR is achieved by maximizing the dissolved calcium concentrations in the soil-water system. This requires the addition of an acid to neutralize the bicarbonate alkalinity, control pH, and maintain the solubility of the added calcium. The approach selected by Fidelity for managed irrigation in the Powder River Basin involves the application of conventional agricultural soil amendments such as elemental sulfur and gypsum (calcium sulfate dihydrate) to the soil.

The elemental sulfur product oxidizes in the presence of air, water, and soil microbial activity to form sulfuric acid, which in turn dissociates to sulfate and hydrogen ions (protons) as follows:

Oxidation of sulfur (S): $S + 1.5O_2 + H_2O = H_2SO_4$

Dissociation of sulfuric acid (H_2SO_4): $H_2SO_4 = 2H^+ + SO_4^{2-}$

Sulfuric acid neutralizes the bicarbonate alkalinity and controls soil pH as follows:

Neutralization of bicarbonate (HCO_3^{2-}): $H^+ + HCO_3^{2-} = H_2O + CO_2$

Gypsum provides dissolved calcium to the soil or water as follows:

Dissolution of gypsum ($CaSO_4.2H_2O$): $CaSO_4.2H_2O = Ca^{2+} + SO_4^{2-} + 2H_2O$

The added calcium effectively competes against sodium for the negatively charged exchange sites on soil clay particles. The positively charged divalent calcium ions (two positive charges) are more strongly attracted to clay particles in soil than are monovalent sodium ions (one positive charge), resulting in a stronger bond between the clay particles. Clay particles that are strongly bound by calcium ions are less likely to swell and disperse.

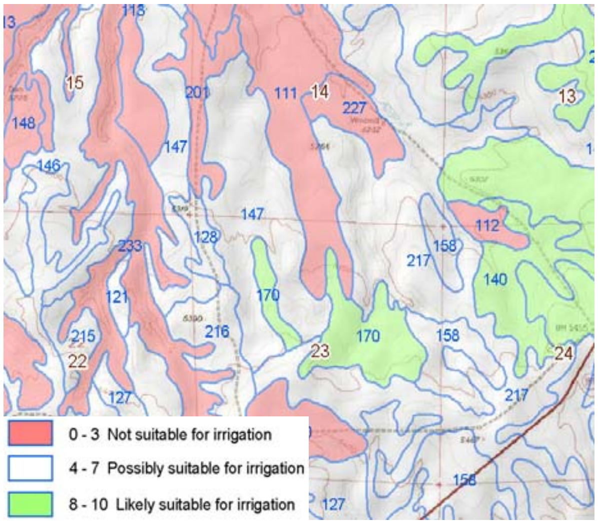
Geochemical equilibrium models such as PHREEQC and MINTEQA are used to calculate the amount of sulfur and gypsum amendments necessary to reduce the SAR of the applied CBNG-produced water to a suitable target level. The quantity of sulfur and gypsum amendments applied to a managed irrigation site depends on the chemistry of the water (i.e., the alkalinity and sodium levels) and the expected quantity of irrigation water necessary to grow the crop. Soil amendment rates for irrigation sites within the Powder River Basin typically range between 0.5

and 1.5 tons per acre per year for sulfur, and 2 and 6 tons per acre per year for gypsum. Soil amendment scheduling is site-specific. Typically, soil amendments are applied directly to the soil in the spring, prior to the initiation of irrigation for the season.

Project Water Balance Estimates

Development of irrigation plans for CBNG-produced water requires a detailed understanding of water production at CBNG project startup and throughout the estimated operational life of the well field. In other words, how much water will we have available from CBNG operations and when will we have it? Estimates of the project water balance are made using spreadsheet-based water balance models. These simulations guide initial irrigation planning, design, and operations.

Site Selection



Candidate irrigation sites are identified in the general area of the CBNG project by screening the soils using geographical information system (GIS) technology and published USDA-NRCS soil survey data. The GIS-based screening examines topography, soil texture, soil permeability, and soil depth to categorize the soils on maps as "very likely suitable," "possibly suitable," and "not likely suitable" for managed irrigation. Other site selection factors include vegetation presently growing on the site, surface hydrology and depth to groundwater, current land use, landowner preferences, and the overall improvement potential (e.g., can the site be improved as in the case of overgrazed upland areas). If the screening demonstrates that there is a high likelihood of suitable soils in the area, a more thorough site and soil evaluation would be required (see below).

Site Characterization

An on-site evaluation of the candidate irrigation site is necessary to determine the specific soil types present, current soil chemical and physical properties, and overall suitability of the site. The on-site evaluation is also necessary to collect soil data to assist in the design of the irrigation system, establish baseline (pre-irrigation) soil conditions, and to meet U.S. Bureau of Land Management (BLM) requirements for produced water management planning.

An Order 1 soil survey (as defined by the USDA-NRCS) is completed for all managed irrigation sites. This equates to approximately one soil profile description test pit per five to ten acres of area investigated (more for highly variable soils, less for more homogeneous soils). Test pits are excavated with a backhoe to a depth of 60 inches. At each test pit, a soil profile description is performed in accordance with USDA-NRCS protocols (Soil Survey Division Staff, 1993). Bulk samples are collected from each soil horizon and submitted to a contract laboratory for analysis of pH, EC, SAR, saturation percentage, ESP, percent lime, percent organic matter (surface horizon only), fertilizer requirements, bulk density, and soil texture (percent sand, silt and clay). In addition, baseline soil infiltration rates are estimated by infiltrometer tests conducted near several of the test pit locations representing each soil-mapping unit.

Crop Selection

Crops typically grown under managed irrigation systems in the Powder River Basin are alfalfa and native forage grass mixes. Crop selection is based primarily on landowner preference, soil type, available equipment for harvesting, and the projected root zone salinity level resulting from the CBNG-produced water in equilibrium with the soil amendments. For alfalfa, the average root zone EC at which alfalfa is expected to begin to decline is 4.0 dS/m (Bridger Plant Materials Center, 1996). Alfalfa can tolerate much higher average root zone EC levels (i.e., up to 8.0 dS/m) before significant yield reductions or mortality occurs. Native forage grass species can typically tolerate much higher average root zone salinity levels than alfalfa. For example, tall wheatgrass can tolerate an average root zone soil EC level of 12 dS/m before yield begins to decline (Bridger Plant Materials Center, 1996).

Most managed irrigation projects are constructed on private land for a landowner who wants and can use the extra forage for livestock. Most of the sites utilized for managed irrigation in the recent past have been overgrazed, upland range areas that support little in the way of native plants. Typically, these sites are vegetated with sagebrush, introduced grass species, prickly pear cactus, and weedy species such as cheat grass. Managed irrigation projects have successfully rehabilitated these small areas into productive forage sources for both livestock and wildlife.

Selection and Design of Irrigation Systems

Several mechanized and non-mechanized irrigation systems are available for applying CBNG water to managed irrigation sites, including center pivot sprinklers, side roll/wheel line sprinklers, hand moved or fixed solid set sprinklers, big gun sprinklers, surface drip, subsurface drip, gated pipe flood, and ditch flood. The preferred system is the center pivot sprinkler because the significant advantages in automation, overall control, runoff control, distribution of water, operation costs, and reliability outweigh the capital costs. The selection of a particular system is based on topography, soil conditions, landowner preferences, size of the site, crop type, post-irrigation land use, available labor, and project economics.

Soil Water Balance Modeling and Irrigation Scheduling

A spreadsheet-based soil-water balance model is used to determine the amount and timing of irrigation required to produce a healthy forage crop and to ensure that sound agronomic leaching practices are followed. With a soil-water balance analysis, all water inputs to the soil and outputs from the soil are identified and balanced according to the following equation (Natural Resources Conservation Service, 2001):

> Total Irrigation Water Applied = Crop Requirement + Leaching Fraction + Irrigation Losses – Precipitation – Change in Soil-Water Content.

For sprinkler irrigation systems, several assumptions, actual data, and calculations are used in developing the soil-water balance and resulting irrigation schedule. Typically, 25 to 30 inches of CBNG-produced water are applied per season to grow crops such as alfalfa and forage grasses in the Powder River Basin.

With irrigation, the EC of the CBNG-produced water by itself should not cause any serious increases in soil salinity. However, amendments applied to the soil to negate the possible effects of the sodicity (SAR) of the produced water will cause an increase in soil EC, requiring leaching with excess water. Salt removal through leaching with excess water is required to minimize the concentration of salts in the root zone. This is termed the “leaching requirement.” In most cases, a leaching requirement (fraction) of 10 to 20 percent will result in a soil EC approximately equivalent to the EC resulting from the equilibration of the produced water with the soil amendments. At the end of each irrigation season, actual (as opposed to projected) soil-water balances are prepared for each irrigation site with site-specific climatic data and total irrigation amounts. These soil-water balances will indicate whether the required leaching fraction has been achieved during the past irrigation season.

Discussion of the soil water balance and the amount of water to be applied to support crop growth and a suitable leaching requirement suggests potential interaction with shallow groundwater. In order for groundwater to be significantly influenced by managed irrigation systems, or any source of water applied to the surface, saturated flow must exist through the soil/unsaturated zone and into the groundwater. As defined above, managed irrigation is not a process whereby water is applied to the ground on a continual basis throughout the year. CBNG-produced water is applied in an agronomic manner, in accordance with crop needs, soil water holding capacities, climatic characteristics, soil infiltration rates, and leaching requirements. Irrigating crops in a way that results in saturating the soil to the point where water is moving in a continuous wetting front under gravity to the groundwater table is not desirable or practical but rather detrimental to vegetation. A continuous wetting front flowing by gravity through soil and bedrock is termed “saturated flow.” When the soil water content is less than saturation, water movement is termed “unsaturated flow.” Water moving through the soil under unsaturated flow conditions moves from areas of higher water content to lower water content, which means water can move diffusely in almost any direction.

Following managed irrigation practices, which utilize the soil-water balance approach to irrigation scheduling, CBNG-produced water is applied in amounts that will be evaporated from the soil and transpired through the roots and out the plant leaves during crop growth. Under these conditions, little or no net movement of water occurs beneath the root zone. As discussed above, additional water is applied during the irrigation season to ensure that salts do not accumulate within the root zone. This leaching requirement typically equates to approximately 5 to 10 inches of additional water spread out over the entire year including precipitation. Therefore, this limited volume of water applied over an entire year is not expected to create saturated flow conditions beneath the root zone down to groundwater. This condition is especially true where irrigation areas are located on upland range sites having significant depth to groundwater.

Irrigation scheduling is critical in minimizing potential runoff and erosion from irrigation areas, and potential runoff/discharge into streams. If irrigation systems were not carefully controlled and monitored, the application rates would exceed the soil infiltration rate. Managed irrigation systems are designed and operated in a way that supplies enough water to meet the demands of the crop, provides for an adequate leaching requirement, and applies water at or below the infiltration rate of the soil.

Water, Soil, Crop, and Meteorological Monitoring

The purpose of the soil, water, crop, and meteorological monitoring plan is to ensure that the managed irrigation site is operated in a manner that (1) promotes the beneficial use of CBNG water to produce forage, (2) maintains soil productivity and sustainability, and (3) minimizes the possible impacts associated with saline and sodic water irrigation. The data collected from soil, water, crop and meteorological monitoring are used to determine the overall performance of the managed irrigation system as well as to make adjustments to irrigation scheduling and soil amendment application rates. Site monitoring documents how the managed irrigation system is performing and data collected during monitoring are utilized in the creation of annual operations and monitoring reports.

Development of Irrigation and Crop Management Plans

The annual irrigation and crop management plan addresses seasonal landowner and land use goals, crop selection, site preparation, seeding, irrigation system operations, harvesting/grazing plans, soil amendment application rates and scheduling, irrigation scheduling, leaching requirements, and monitoring. This document serves as the overall planning, operations, and monitoring guide. The irrigation and crop management plan is revised each winter based on the monitoring results and other input from the previous irrigation season, and the operational requirements for the upcoming irrigation season.

Site Closure Planning

A critical component of the managed irrigation planning process is site closure. Issues to be addressed during site closure planning are:

- What are the post-irrigation land use goals and landowner preferences?
- Will the site continue to be cropped or will it be put back into native vegetation?
- Will the irrigation equipment be removed or will it be left in place to be used by the landowner?
- If the irrigation equipment is to remain, what are the water sources available for continued irrigation?
- What do we expect in the way of post-irrigation soil physical and chemical conditions?
- Will the chemistry of the soil require adjustment to meet post-irrigation land use and landowner goals?

- What level of post-irrigation monitoring will be required to meet post-irrigation land use and landowner goals?

Some of the answers to these questions can be anticipated at project startup, while others can be answered only after conducting and evaluating the managed irrigation activities. In any event, the primary goal of site closure is to leave a physically and chemically stable site capable of moving towards a sustainable vegetative community that meets or exceeds landowner goals.

Conclusions

The production of natural gas in the Powder River Basin of Montana and Wyoming and the concurrent production of unaltered groundwater are occurring in a region that is naturally arid during a time of unprecedented drought. Research and development programs and full-scale irrigation projects have demonstrated that CBNG water can be beneficially used to grow forage where there was none, while protecting the soil resource. Since Fidelity first embarked on developing this process for beneficially using produced water, several other CBNG producers in the Powder River Basin have added managed irrigation to their water management "tool kit." Two to three tons per acre of alfalfa are routinely produced with CBNG irrigation water in the Powder River Basin of Wyoming. Managed irrigation has evolved into a practice that is based on established soil science, water chemistry, and agronomic principles, and should be evaluated as a water management and beneficial use alternative on a project- and site-specific basis.

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