Technical Memorandum

To: Dan Arthur/ALL

From: Brian Bohm and Dr. David Epperly/ALL

Date: 12/5/2005

Re: Talking Points on Managed Irrigation with CBNG Produced Water in the Powder River Basin.

Dan,
Per your and the MBOGC request, Dr Epperly and I have prepared the following discussion/talking points on the use of CBNG produced water for Managed Irrigation activities in the Powder River Basin. The following presents various questions and answers obtained from a variety of sources from several researchers who are performing work on the use of CBNG produced water in the PRB.

What is coal bed natural gas produced water?

Coal bed natural gas (or CBNG) produced water is naturally occurring groundwater that is withdrawn from a coal seam to facilitate the production of natural gas from the coal seam. The presence of this groundwater in the coal seam acts to trap the natural gas within the coal; in order to allow this natural gas to be released (produced) from the coal seam some of the water must be removed from the coal seam. Prior to withdrawal the groundwater creates a pressure with the coal seam which acts to hold the natural gas in place. Once this pressure is removed (by withdrawing some of the groundwater) the natural gas is released from the coal and can migrate to the wellbore.

How is CBNG produced water different from surface water or other groundwaters?

All waters (surface or ground) have natural chemical variations that result from the interaction of these waters with the soils, minerals, and rocks present at the surface or in the subsurface environment from which they are in contact. Groundwater and surface waters are typically evaluated by hydrologists and hydrogeologists by the quantities of the most common four positively charged cations (calcium, sodium, magnesium, and potassium) and the most common four negatively charged anions (bicarbonate, carbonate, chloride and sulfate). CBNG produced water within the PRB typically exhibits a sodium/bicarbonate water signature, meaning that Sodium is most abundant cation, and bicarbonate is the most abundant anion. While shallow alluvial groundwaters can range from calcium/bicarbonate to sodium/sulfate, surface waters in the PRB range from calcium/bicarbonate to sodium/chloride-sulfates. Agronomists and soil scientist use another method of classifying waters, they evaluate the total dissolved solids (TDS) concentrations (as measure of the salinity) and the sodium adsorption ratio (SAR) which is a measure of the sodicity of the water, these two values are used to evaluate the irrigation quality of water.

What is the Sodium Adsorption Ratio and what does it tell us about water quality?

Sodium Adsorption Ratio (SAR) is a comparison of the relative concentration of Sodium cations to the relative concentrations of Calcium and Magnesium cations present in water. SAR is calculated using the following formula (all values are in meq/L):

$$SAR = \frac{Na}{\sqrt{\frac{Ca + Mg}{2}}}$$

The important thing to understand about SAR values is that this number is not a measure of the concentration of sodium but a measure of the relative concentration of sodium compared to the concentrations of calcium and magnesium. A groundwater with 500 mg/L sodium can have an SAR of 19 or an SAR of 5 depending on the relative quantities of calcium and magnesium. The SAR relationship is not linear, therefore in the example given an SAR of 19 which is nearly four times greater than an SAR 5 does not mean the relative concentrations of Ca and Mg is four times greater for the SAR 5 water. This difference in SAR equates to a difference in the calcium and magnesium concentrations present is 14.4 times greater in the SAR 5 water than the SAR 19 water. Waters which have a high SAR are described as Sodic, indicating these soils have a higher percentage of dissolved sodium than calcium and magnesium.

Why is Sodicity a concern for Irrigators?

Sodicity is a concern because of three primary affects sodic irrigation water can have on the physical properties of soil: dissolved sodium in irrigation water can cause dispersion of soils which reduces infiltration of water, reduces the hydraulic conductivity, and surface crusting in clay rich soils. 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. Put another way, certain clay minerals are more prone to “swelling” as a result of the incorporation of sodium ions (which are larger than calcium or magnesium ions) into the inter sheet layers of the clay mineral. As an example, imagine two sheets of construction paper (clay sheets) with several baseballs (calcium ions) sandwiched between the two sheets, if the baseballs were replaced by basketballs (sodium ions), the space occupied by the two sheets would increase by difference of the diameters of two types of balls. Now if a room was half full of baseball filled sheets (calcium rich clays) and all the baseballs were replaced the basketballs, the room would be now full of basketball filled sheets (sodium rich clays) and the amount of free space to move through the room would effectively be lost. The replacement of calcium ions by sodium ions in clay rich soils results in a similar loss of soil pore space and results in a “swelling” of the clay minerals. In general, soils with moderately high, to high, clay contents are at higher risk.

Additionally, as these salts accumulate in the area near the plant’s root (or the soil root zone), the precipitated salts can impeded the movement of water or change the structure of soil. The cations present in salts affect the physical properties of some of soil particles, in particular clay particles are affected the most by certain cations. Clay particles are composed of negatively charge sheets with cations present along the surface, as more cations are present in the soil water the attraction between clay sheets increases resulting in the flocculation or binding of clay particles. The flocculation of clay particles results in decreased pore space between the particles decreasing the movement of soil water, this can have both a positive and negative impact in that flocculate soils are more stable and less likely to erode but flocculated soils also reduce the ability for water to migrate within the soil.

What is Total Dissolved Solids and what does it tell us about water quality?

Total dissolved solids (TDS) is a measure of the relative concentration of dissolved salts present in a water or a measure of the salinity of the water. It is important to realize that “salts” in this context refers to dissolved cations and anions which typically include: calcium, sodium, magnesium, potassium, carbonate, bicarbonate, chloride, and sulfate and is not just in reference to common “table salt” (NaCl). The Environmental Protection Agency defines potable drinking water as having a TDS of less than 500 mg/L, the USGS defines freshwater as having <1,000 mg/L TDS, and typical seawater has a TDS of approximately 35,000 mg/L. Salinity (or TDS) is often estimated by measuring the electrical conductivity (EC) of a water, TDS can be approximated from EC (expressed in units of dS/m or mmhos/cm) by multiplying the EC value by the conversion factor of 640 (Hem, 1992).

Why is Salinity a concern for Irrigators?

Salinity and salts affect plant growth over time because plants uptake water, but most crop plants typically do not uptake the salts, thus when saline water is present the plants are required to expend more energy to separate the water from the salt causing additional stress on the plants. Over time there can be an accumulation of salts near the plant roots if there is inadequate flushing of the soils which increases the amount of energy a plant must expend to obtain the water.

Plant species vary with respect to salt tolerance. Generally, most forage and field crops grown in southeastern Montana and northeastern Wyoming are semi-tolerant to tolerant for salt. For example, based on research presented in the Montana State University Extension Montguide #8382, the EC Tolerance of four common crops (wheat, oats, safflower, and corn) is between 4.0 and 10 dS/m (Montana State University Extension Salinity, Sodic Water and Soils FAQ, 2005). Other crops such as barley, sugar beet, and sunflower are tolerant to EC's higher than 10 dS/cm, while potatoes, field bean, peas, and lentils are less tolerant and can be affected by EC's < 4dS/cm.

Is CBNG Produced Water Saline or Sodic?

Coalbed natural gas produced water has been shown to vary considerably across the PRB and between the various coal seams in any area of the PRB. Generally, CBNG produced water increases in salinity and sodicity as you move north and west across the basin and with depth in a particular area of the PRB. The coal seam waters of the PRB vary from SAR values of < 5 to SAR values greater than 50, while TDS values range from less than 500 mg/L to more than 10,000 mg/L. The University of Wyoming calculated a median SAR for coal seams in the Fort Union Formation of the PRB of 9 (unitless) and a median TDS of 1,100 mg/L. These median values are under the U.S. Department of Agriculture's definitions of saline (E.C. of 3.0 dS/m or ~1,920 mg/L TDS) and sodic (SAR >12).

What are the relationships of Sodic (SAR) and Saline (EC) water when used with irrigation on soils?

Sodium and salinity are different issues. Sodium at high levels can affect soil permeability and infiltration. Sodium can exaggerate the shrink/swell character of a soil and can slow infiltration, thereby increasing runoff. Soils can have problems with sodium but not salinity. Soil hydraulic properties (ability to infiltrate water) improve with increasing salinity (that is, increasing EC), no matter the SAR. Put another way, for a given SAR, infiltration rates generally increase as salinity (measured by the EC) increases. Soil hydraulic properties degrade with increasing SAR, no matter the salinity. In the long run, soil EC and SAR will be determined by the EC and SAR of the irrigation water.

What is Managed Irrigation and how does it facilitate the use of saline or sodic waters for irrigation?

Managed irrigation has been defined as the application of soil science, water chemistry, and agronomic principles to manage the application of irrigation water in a beneficial manner to produced forage for livestock and wildlife while protecting soil physical and chemical properties (Harvey, 2004). Managed irrigation 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. 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.

What are the primary components of Managed Irrigation?

The primary components of the managed irrigation process are as follows (taken from Harvey and Brown, 2005):

- 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

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. 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 most popular approach 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 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 be available from CBNG operations and when will it be available? Estimates of the project water balance can be 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. One of the preferred systems 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 can be 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.

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.

Has Managed Irrigation been successful using CBNG-produced water?

There have been several producers that have been very successful using CBNG water for irrigation. DeJoia (2002) reported on a feasibility study from the fall of 2001 and the 2002 operating year that demonstrated CBNG produced water irrigation can be managed effectively without causing soil degradation. The results of the project indicated that the use of soil applied amendments was successful at mitigating the high bicarbonate and sodium concentrations in CBNG produced water. The addition of gypsum and sulfur appeared to work the best out of all of the treatments applied. These amendments appeared to work best when a one-month application was applied versus the use of a three-month application. Gypsum alone also appears to be an option; however, because of the larger amounts required to treat this water with gypsum alone, the treatment costs are higher. Therefore the addition of sulfur was able to reduce the total amendment cost while not impacting the effectiveness of the amendments. No other treatments appeared to effectively control soil SAR at the site. The SAR of the soil ranged from 8.6 to 14.6 with an average SAR of 12.0. Although these levels were elevated they did not appear to impacting soil infiltration rates.

Several other CBNG producers have used Managed Irrigation with very positive results. One other example is the use of subsurface drip irrigation (SDI) by J.M. Huber at Prarriedog Creek, Wyoming. They are irrigating 115 acres of alfalfa using SDI and applying up to 60 inches of water per year. The water is being applied at or below the root zone with the salts mostly going below the root zone. The soils at the site have a high porosity and they perform some leaching. The yield of the alfalfa has increased with the use of SDI and there have not been any signs of significant impacts to plants or soils.

The Agronomic Monitoring and Protection Program (AMPP) is a soil and crop testing program developed by Fidelity to better understand the potential effects of CBNG production on the soil and crops in the Tongue River drainage area of southeastern Montana. Data collected through this program creates a baseline of information to determine what — if any — impacts occur from the discharge of water produced in association with CBNG development. The AMPP started collecting data on soils irrigated with CBNG in the fall of 2003 and finished this stage of data collection this last fall, with further data collection to follow. The final report has not been released, but the information to-date indicates discharge of unaltered groundwater into the Tongue River has not had and will not have a negative impact on irrigated lands.

What is the best type of irrigation system to use with CBNG produced water?

The main types of irrigation used with CBNG produced water are sprinkler (center pivot, side roll, big gun, solid set), flood, and subsurface drip irrigation. Each type of irrigation has its advantages and disadvantages depending on the crop, application rate, soil type, topography, and required labor. Therefore, there is not one system that is better than others and should be chosen based on these factors, cost and the landowner's input. All managed irrigation solutions are site specific. The design approach, amendment application rate, and water application equipment selected for a particular project are unique to the water and soil chemistry of the location.

What affect will Managed Irrigation have on 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.

Will Managed Irrigation cause salt damage on the surface of the ground?

Where land is irrigated year round and not allowed to dry out, salts can migrate up. Seasonal precipitation flushes salts down through the soil, often to depths of 1-1.5 meters below the root zone of most crops. Wet years move the salts down deeper. Seasonal dry periods slow the ability of salt to migrate up into the root zone of plants.

What is PAM and does it help with soil infiltration?

Polyacrylamide (PAM) is a synthetic water-soluble polymer made from monomers of acrylamide. PAM binds soil particles together. Surface application of PAM in solution has been found to be very effective in decreasing seal formation, runoff, and erosion and have been known to benefit soil properties for a long time. DeJoia (2002) reported from their studies that use of soil PAM did not appear to control soil pH or sodicity, however, the infiltration did remain relatively high. The infiltration rate was actually as good as the gypsum and sulfur site. Therefore, it appears that the use of soil PAM could help to increase infiltration rates on soils that are adversely affected by low infiltration. They added that actual implementation of soil PAM for this practice was not evaluated so its actual place in managing CBM produced water is not known at this time.

What are some estimated costs for using Managed Irrigation with CBNG-produced water?

Costs for managed irrigation systems are influenced by water chemistry, soil chemistry, water volume, irrigation season limitations and land management practices. Paetz and Maloney (2002) gave an example of costs for a Managed Irrigation project in the Powder River Basin. Based on the evaluation of an actual managed irrigation site with a flow of 12,500 barrels per day (bbl/day), the lifetime cost of a 100-acre system was $0.005 to $0.01 per barrel for design and equipment; $0.04 to $0.06 per barrel for water amendments; and $0.02 to $0.04 per barrel for operation and monitoring for a total project cost of $0.06 to $0.11 per barrel.

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