

# Oil & Natural Gas Technology

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## Final Technical Report

### **Evaluation of Phytoremediation of Coal Bed Methane Product Water and Waters of Quality Similar to that Associated with Coal Bed Methane Reserves of the Powder River Basin, Montana and Wyoming**

Submitted by:

James W. Bauder, Ph.D.

Department of Land Resources and Environmental Sciences

334 Leon Johnson Hall, Montana State University

Bozeman, MT 59717-3120

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Office of Fossil Energy



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**Author: James W. Bauder, Ph.D.**

**Department of Land Resources and Environmental Sciences  
Montana State University  
334 Leon Johnson Hall, Montana State University  
Bozeman, MT 59717-3120**

United States Department of Energy  
National Energy Technology Laboratory  
3610 Collins Ferry Road  
P.O. Box 880  
Morgantown, WV 26507-0880

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## ABSTRACT

U.S. emphasis on domestic energy independence, along with advances in knowledge of vast biogenically sourced coalbed methane reserves at relatively shallow sub-surface depths with the Powder River Basin, has resulted in rapid expansion of the coalbed methane industry in Wyoming and Montana. Techniques have recently been developed which constitute relatively efficient drilling and methane gas recovery and extraction techniques. However, this relatively efficient recovery requires aggressive reduction of hydrostatic pressure within water-saturated coal formations where the methane is trapped. Water removed from the coal formation during pumping is typically moderately saline and sodium-bicarbonate rich, and managed as an industrial waste product. Current approaches to coalbed methane product water management include: surface spreading on rangeland landscapes, managed irrigation of agricultural crop lands, direct discharge to ephemeral channels, permitted discharge of treated and untreated water to perennial streams, evaporation, subsurface injection at either shallow or deep depths.

A Department of Energy-National Energy Technology Laboratory funded research award involved the investigation and assessment of: 1) phytoremediation as a water management technique for waste water produced in association with coalbed methane gas extraction; 2) feasibility of commercial-scale, low-impact industrial water treatment technologies for the reduction of salinity and sodicity in coalbed methane gas extraction by-product water; and 3) interactions of coalbed methane extraction by-product water with landscapes, vegetation, and water resources of the Powder River Basin.

Prospective, greenhouse studies of salt tolerance and water use potential of indigenous, riparian vegetation species in saline-sodic environments confirmed the hypothesis that species such as Prairie cordgrass, Baltic rush, American bulrush, and Nuttall's alkaligrass will thrive in saline-sodic environments when water supplies sourced from coalbed methane extraction are plentiful. Constructed wetlands, planted to native, salt tolerant species demonstrated potential to utilize substantial volumes of coalbed methane product water, although plant community transitions to mono-culture and limited diversity communities is a likely consequence over time. Additionally, selected, cultured forage quality barley varieties and native plant species such as Quail bush, 4-wing saltbush, and seaside barley are capable of sustainable, high quality livestock forage production, when irrigated with coalbed methane product water sourced from the Powder River Basin. A consequence of long-term plant water use which was enumerated is elevated salinity and sodicity concentrations within soil and shallow alluvial groundwater into which coalbed methane product water might drain. The most significant conclusion of these investigations was the understanding that phytoremediation is not a viable, effective technique for management of coalbed methane product water under the present circumstances of produced water within the Powder River Basin. Phytoremediation is likely an effective approach to sodium and salt removal from salt-impaired sites after product water discharges are discontinued and site reclamation is desired.

Coalbed methane product water of the Powder River Basin is most frequently impaired with respect to beneficial use quality by elevated sodicity, a water quality constituent which can cause

swelling, slaking, and dispersion of smectite-dominated clay soils, such as commonly occurring within the Powder River Basin. To address this issue, a commercial-scale fluid-bed, cationic resin exchange treatment process and prototype operating treatment plant was developed and beta-tested by Drake Water Technologies under subcontract to this award. Drake Water Technologies secured U.S. Patent No. 7,368,059-B2, “Method for removal of benevolent cations from contaminated water”, a beta Drake Process Unit (DPU) was developed and deployed for operation in the Powder River Basin. First year operation demonstrated an 84% sodium removal capacity.

Greenhouse, laboratory and field research documented substantial likelihood of measurable alteration in soil chemistry, soil physical properties, and shallow alluvial aquifers in and below areas of sustained surface application through irrigation or water spreading or impoundment of coalbed methane product water in evaporation reservoirs within the Basin. Events of repeated wetting and drying of agricultural soils characteristic of the Powder River Basin with coalbed methane product water, followed by infrequent rainfall events, presents high probability circumstances of significant reductions in infiltration capacity and hydraulic conductivity of agricultural soils containing more than 34% smectite clay. Soil solution extract salinities under such conditions are likely to equilibrate at levels 2-3 times greater than the salinity of the coalbed methane product water being applied while sodicity is likely to equilibrate at levels approximately equal to the coalbed methane product water. In field situations where evaporation storage impoundments are constructed overlying non-dispersive soils, pit-bottom infiltration with subsequent down-gradient discharge as surface seepage is a possible occurrence within the Powder River Basin. This is due primarily to the geologic configuration of soil and bedrock materials within the Basin. Additional studies demonstrated that pre-impoundment and landscape management practices are important to the preservation or restoration of soil quality post-development. Within the semi-arid landscapes of the Powder River Basin, topsoil preservation allowing for replacement cover soil to depths of approximately 30 cm, augmented by supplemental water, may be necessary for adequate rangeland restoration within the Powder River Basin post coalbed methane extraction.

Time-series analysis of water quality parameters of the Little Powder River, a prairie stream transitioning from ephemeral to perennial through the northeastern portion of the Powder River Basin indicated trends of elevated sodium concentration, sodium-to-calcium and magnesium ratios, and salinity between the pre-coalbed methane development period and the initial years of coalbed methane development within the Basin. These increases were most evident during the months of May through December. However, based on the limited amount of data, the lack of pre-development baseline characterizations, and the varied results from the time-series assessments of records of the Little Powder River, it was difficult to conclude definitively whether or not coalbed methane product water of sufficient volumes was reaching the Little Powder River and thereby altering the chemistry of this tributary to the Powder River.

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## **Preface**

The production of coalbed methane (CBM), also referred to as coalbed natural gas (CBNG) involves extracting natural gas from buried coal deposits. CBM has become a promising energy source for the nation, now accounting for about one-twelfth of U.S. natural gas production. The contiguous U.S. is estimated to contain 700 trillion cubic feet (Tcf) of CBM. And because most coal beds are so methane rich, a cubic foot of coal can contain six or seven times the volume of gas that is contained in traditional natural gas reservoirs. Experts estimate that CBM will play an even more significant role in the nation's energy future.

Today, one of the most active "plays" lies in the Powder River Basin, a geologic bowl stretching from Glenrock, Wyoming, to the Yellowstone River, and from Gillette, Wyoming, to the foothills of the Bighorn Mountains. The U.S. Geological Survey estimated in 2001 that the amount of recoverable CBM in the Powder River Basin ranges from 8.24 Tcf to 22.42 Tcf. A recent environmental impact statement projected 2.5 Tcf of recoverable CBM in the Montana portion of the Basin. The Montana Bureau of Mines and Geology and the U.S. Department of Energy arrived separately at an estimate of .8 to 1 Tcf of recoverable gas in the same area.

Between 1997 and 2007, the number of producing CBM wells in the Powder River Basin increased from 360 to more than 22,000. Unlike "traditional" natural gas, CBM production is associated with large volumes of water and economically viable and recoverable reserves occur relatively close to the earth's surface. Extracting CBM from shallow coal seams is accomplished by reducing water pressure responsible for methane adherence to coal particles within saturated coal seams. Water pressure prevents the methane from escaping into the air or surrounding soil. When the water pressure is reduced, the methane detaches from the coal and forms recognizable bubbles of gas. Pumping water from methane-rich coal seams stimulates this detachment process.

Management of ‘produced water’ associated with CBM recovery in Montana’s Powder River Basin has been an issue of environmental concern since the onset of large-scale CBM recovery. Experts estimate that 0.25 million acre feet of water will be produced annually for the first 7 to 10 years of development. With 7,000 to 10,000 wells projected for Montana, pumping could spread an additional 100,000 acre feet of water a year over the Yellowstone River watershed.

The principal environmental process contributory to CBM development is microbial-facilitated biogenesis, with the predominant equilibrium products being methane and carbon dioxide. Subsequent to the biogenesis process, evolved carbon dioxide transforms to bicarbonate as the principal anion present within the coal seam where the methane resides, while the principal cation is sodium. Consequently, produced water from CBM development is typically alkaline, saturated with respect to sodium bicarbonate, and essentially devoid of calcium and magnesium. With respect to most perennially flowing surface waters within the Powder River Basin, CBM product water is considered to have substantially elevated sodium concentration and overall salinity.

Current strategies for CBM produced water management include containment in infiltration and evaporation ponds, land spreading, limited irrigation, subsurface shallow and deep injection, and discharge to existing streams. Because of environmental concerns about direct discharge of CBM production water into ephemeral and perennial streams of the basin, concerns about perceived waste of the water resource, and concerns about loss of native rangeland to evaporation ponds, increasing attention is being given to proposals for beneficial use of CBM-produced water for irrigation, for ephemeral and perennial stream flow augmentation and habitat enhancement, and for augmentation of limited irrigation water supplies.

This final report summarizes the outcomes and findings of an extensive suite of prospective field, greenhouse, and laboratory studies focused on characterization and management of interactions between CBM-product water and soil, water resources, and vegetation in the Powder River Basin. Initially, the primary focus of research supported by DOE-NETL award DE-FG26-01BC15166 was that of evaluating the potential for phytoremediation of CBM product water and waters of quality similar to that associated with CBM reserves of the Powder River Basin, Montana and Wyoming. Phytoremediation is defined as the process of using plants for treatment (sodium salt removal, in the case of CBM product water) of soil or water. Complimentary undertakings included investigation of feasibility of agronomically beneficial use of CBM product water, i.e., irrigation and enhanced livestock forage production, resin-exchange technologies for economically viable treatment of CBM product water to accomplish sodium reduction, characterization of soil responsiveness to CBM product water spreading, and characterization of the hydraulic properties associated with CBM storage and infiltration impoundments.



## Summary of Methods and Conclusions

### Phytoremediation of Coalbed Methane Product Water

**Water use potential and salt tolerance of riparian species in saline-sodic environments.** A prospective, greenhouse study was initiated to assess the potential of beneficial utilization of CBM product water in constructed wetlands settings. Prospective studies are characterized as investigations of responses to study candidates following the onset of rigorously controlled study conditions, i.e., in this case – candidate plants for constructed wetlands wherein the primary source of inflow water is CBM product water. This approach allows for well-defined study protocols of a proposed beneficial use of CBM product water. Riparian plant species, native to Montana and Wyoming and classified as halophytes, were selected as study candidates. Halophytes are plants characterized by ability to live in saline conditions and/or adapted to living in saline environments; additionally, halophytes are considered to be plants that accumulate high concentrations of salt in plant tissue. Species chosen for this study were subjected to salinity-sodicity conditions designed to mimic a ‘reasonably representative’ CBM product water of the Powder River Basin. Halophytes were grown to maturity in simulated wetland conditions. Water use rates, resulting wetland water chemistry, halophyte biomass production, forage value (quality with respect to livestock and wildlife feed), and salinity tolerance of each species were monitored throughout the study period and at the conclusion of the study. Plant species included in the study were:

American bulrush	<i>Scirpus americanus</i> Per.
Maritime bulrush	<i>Scirpus maritimus</i> L. var. <i>paludosus</i> (A. Nels.) Kuek
Nuttall’s alkaligrass	<i>Puccinellia nuttalliana</i> (Schult.) Hitche
Prairie cordgrass	<i>Spartina pectinanta</i> Link
Inland saltgrass	<i>Distichlis spicata</i> (L.) Greene
Baltic rush	<i>Juncus balticus</i> Willd
Common cattail	<i>Typha latifolia</i> L.

Water use rates of mature plants exceeded reference evaporation rates over a range of salinities for most species. Relatively high water use rates were attributed to turbulent air flow and high diffusion rates, both conditions which would likely occur in constructed wetland settings within prairie landscapes of the Powder River Basin. For high water use species, ratios between plant water use rates and reference evaporation exceeded 3.0 at lower salinities.

Biomass production of indigenous wetland species declined following defoliation and as wetland source water salinity increased, due primarily to evapoconcentration. Grass species increased biomass production following defoliation and under elevated salinity conditions. Crude protein, and index of forage quality, decreased with progressive harvests of the indigenous wetland. Based on percent acid detergent fiber and crude protein, forage value (the combination of yield

and quality) of most of the species studied was equal to or greater than average grass hay forage value.

- **Conclusion:** Wetlands constructed of species studied will thrive in saline-sodic conditions when water supplies are plentiful. Correspondingly, these indigenous wetland species will outperform or perform similarly to evaporation ponds for CBM product water management and disposal, while providing forage resources, beneficial uses, and potential for biofuel feedstocks. Such wetlands may serve as scattered micro-sites for terrestrial carbon sequestration through anoxic organic matter accumulation.
- **Conclusion:** Prairie cordgrass, Baltic rush, American bulrush, and Nuttall's alkaligrass appear to be suitable species for product water disposal and beneficial use through constructed wetlands. Of the species studied, only common cattail showed physical signs of salinity stress over the experimental period, proving that species examined are tolerant of saline-sodic conditions common to CBM product water in the Powder River Basin. Similarly, these species can survive concentrations of salts likely to accumulate in wetlands created by discharge of CBM product water.

**Effects of irrigation water quality and water table position on plant biomass production, crude protein, and base cation removal.** A prospective, greenhouse study was initiated to examine the effects of surface irrigation water quality (comparable to CBM product water quality) and water table position on the ability of selected plant species to produce biomass and crude protein, and to phytoremediate shallow groundwater of the base cations sodium ( $\text{Na}^{+1}$ ), calcium ( $\text{Ca}^{+2}$ ), and magnesium ( $\text{Mg}^{+2}$ ). Water qualities simulating coalbed methane product water and irrigation-season Powder River water were used as the source waters. Through controlled irrigation, study column water tables were maintained at depths representing shallow, intermediate, and deep water table positions. Plant communities consisted of one of three indigenous halophytes, either Wytana fourwing saltbush (*Atriplex X aptera* A. Nels. (pro sp.)), big saltbush (*Atriplex lentiformis* (Torr.) S. Wats.), or maritime barley (*Hordeum marinum* Huds.). These species were selected for study based on the potential livestock forage quality and salt tolerant (halophytic) characteristics.

Salinity and sodicity of shallow groundwater increased progressively over time, reflecting a net accumulation of salt within shallow groundwater, despite some salt removal by canopy harvest. Increase in salinity was directly correlated with salinity of source water, plant water use, and groundwater depth. Greatest increases in salinity and sodicity were measured in situations of shallowest water table, reflecting poor drainage conditions. This circumstance of shallow water table also resulted in greatest biomass production.

The investigation revealed positive and negative attributes of each species in these circumstances, suggesting species proposed for irrigation with modestly saline x modestly sodic water or phytoremediation of salinity and sodicity sourced from CBM product water should be chosen based on their individual abilities to produce desired outcomes. Significant differences in effects of salinity and sodicity on species were measured. Biomass production was the most

evident difference among the species. Production of *H. marinum* exceeded that of either *Atriplex* spp. by ~80-120%, on a dry mass basis. However, forage potential needs to be assessed on both a quantity and quality basis. While *H. marinum* biomass production exceeded that of *Atriplex* spp., the former contained only 11% crude protein, compared to 16% in *A. lentiformis* and 14% in *Atriplex X aptera*. Thus, forage needs of wild and domestic animals and the potential for use of the species of this study for phytoremediation or beneficial water use need to take into account salt tolerant plant species' abilities to efficiently produce both biomass and crude protein.

- **Conclusion:** Salinity thresholds for the three study species were not exceeded during the experimental period, even though current irrigation water quality standards adopted in Montana were exceeded. There were no measured significant differences in biomass production, crude protein production, or cation uptake on a mass basis as a consequence of water quality treatments. *Hordeum marinum* removed only one-third the mass of base cations removed from shallow groundwater by *A. lentiformis* and slightly more than one-half the cation mass removed by *Atriplex X aptera*. *A. lentiformis* accumulated approximately 4 times the base cations of that of *H. marinum* on a percent basis and 1.5 times that of *Atriplex X aptera*. Thus, if removal of large quantities of salts is the primary management goal, *A. lentiformis* cation removal significantly exceeded that of either *Atriplex X aptera* or *H. marinum*.
- **Conclusion:** Calcium and  $\text{Na}^+$  uptake data identified significantly different responses of each species to water table depth. Regardless of irrigation water quality or species, plants in columns with the water table maintained at the 0.38 m depth accumulated significantly greater percentages of  $\text{Na}^+$  (on a dry mass basis) in above-ground biomass than did plants grown in columns with deeper water tables. In contrast,  $\text{Ca}^{2+}$  uptake was generally least in those columns with the water table maintained at the 0.38 m depth. The shallowest water table depth appeared to maximize  $\text{Na}^+$  uptake, while minimizing  $\text{Ca}^{2+}$  uptake, one might expect groundwater SAR to diminish with increasingly shallow water table depth. However, the opposite is true, presumably because enhanced biomass production with the water table maintained at 0.38 m depth led to greater ET and correspondingly greater amounts of irrigation water applied than that applied to columns with the water table maintained at a deeper depth. It appeared that although plants grown with the 0.38 m water table depth accumulated  $\text{Ca}^{2+}$  and  $\text{Na}^+$  in proportions favorable to decreased groundwater SAR, they simply could not remove cations at a rate equal to that added by the irrigation water.
- **Conclusion:** When choosing among *Atriplex lentiformis*, *Atriplex X aptera*, and *Hordeum marinum*, the former species provides the greatest overall benefit in phytoremediation of modestly saline-modestly sodic water. Compared to the other species, *A. lentiformis* had the greatest percent crude protein in its biomass, the greatest cation uptake on both a percent and mass basis, and resulted in the lowest post-irrigation saturated soil solution EC and SAR, making it a desirable choice among the three species studied for use in modestly saline-modestly sodic situations similar to this study.

**Assessing constructed wetlands for beneficial use of saline-sodic water.** A field study was completed using 12 constructed wetland environments to evaluate the utility of wetland sites as a beneficial use management option and phytoremediation approach for CBM product water. Field site visits and reconnaissance assessments of ephemeral stream channels where CBM product water is being managed in the Powder River Basin revealed that native plant species (primarily halophytes) establish communities which are hydrologically regulated and different from communities in ephemeral channels prior to CBM product water discharges. Nine ephemeral environment plant species were segregated into three communities and established in replicated, constructed wetland communities. Closed-system wetland cells were constructed and supplied with water which was reflective of Powder River Basin CBM product water chemistry. Chemistry of the supply water was sodic and moderately saline ( $EC \sim 3.4 \text{ dS m}^{-1}$ ,  $SAR > 25$ ).

All three communities had similar total water use but water use efficiencies differed significantly among the communities. This difference was attributable to distinct differences in biomass production and accumulation. Species survival and colonization during the first 24 month period was very good for seven of the nine species studies. American bulrush (*Scirpus americanus*) had very sparse spring regrowth and inland saltgrass (*Distichlis stricta*) was likely out-competed by creeping spikerush (*Eleocharis palustris*).

Evapoconcentration of salts sourced from CBM product water resulted in significant increases in soil SAR and EC, which occurred in the top 6 inches of soil. SAR increased 20-30 fold, from pre-existing conditions, while salinity (EC) increased 8-10 fold increase. Under circumstances where amendments (gypsum and sulfur) were surface-applied to mitigate sodium-induced dispersion, salinity and sodicity of shallow alluvial groundwater increased subsequent to irrigation and abandoned irrigation sites became both sodic and saline over time. In all circumstances where CBM produced water was used to supply water to constructed wetlands of historically non-irrigated alluvial channel soils, surface soil salinity increased. In some instances, subsurface salinity decreased due to leaching of geologic accumulations below the root zone.

- **Conclusion:** Constructed wetlands planted to native, salt tolerant species have potential to utilized substantial volumes of CBM product water, although plant community transition is likely to progress from communities of diverse composition to mono-culture or limited diversity communities.
- **Conclusion:** Evapoconcentration of salts in hydrologically closed-system, constructed wetlands for CBM product water management ultimately leads to adverse soil salinity and sodicity conditions, limited wetland species viability, and challenges of reclamation or restoration to pre-disposal conditions.
- **Conclusion:** An initial comparison of pan evaporation to plant community evapotranspiration indicated a free water surface associated with lined impoundments of CBM product water may provide a more effective and efficient means of reducing the volume of produced water associated with CBM development than will constructed wetlands.

- **Conclusion:** Maritime bulrush (*Scirpus maritimus* L. var. *paludosus* (A. Nels.) Kuek), Baltic rush (*Juncus balticus* Willd), creeping spikerush, and Canada wildrye appear to be species which are readily adaptable as revegetation species in wetland areas impacted or influenced by CBM product water. American bulrush (*Scirpus americanus* Per.), inland salt grass (*Distichlis spicata* (L.) Greene), alkali grass (*Puccinellia nuttalliana* (Schult.) Hitchc), and prairie and alkaline cord grasses (*Spartina pectinanta* Link ) dominated ephemeral channels where PRB CBNG produced water was discharged for extended periods of time.

**Commercial hay barley production potential with CBM product water.** Three years of field x greenhouse study were completed in grow-out, rainout shelters constructed at Montana State University-Bozeman. Fourteen Montana adaptive forage barley (*Hordeum vulgare* subsp. *vulgare*) varieties were successfully grown to full season, harvested and analyses for yield, forage quality, performance characteristics including salinity tolerance, in replicated field trials. Forage barley production under full season irrigation with simulated CBM product water equated to approximately 80% of forage production of same varieties under full season non-CBM water irrigation, with some measurable quality reductions. Total seasonal plant consumptive use (averaged across all varieties) was determined to be 2.9 acre feet/acre (34.8 inches) with 10% salt leaching allowance. Shallow alluvial groundwater salinities increased from 1.3 dS/m (~830 mg/l Ca-Mg SO<sub>4</sub> and CO<sub>3</sub>) under non-CBM irrigated lysimeters to 2.8 dS/m (~1792 mg/l Na<sub>2</sub>SO<sub>4</sub>). Salt tolerant hay (livestock forage) barley varieties were identified and ranked with respect to production potential and suitability to sites where CBM product water had previously been applied in a land-disposal technique. These varieties have the potential to serve as reclamation and restoration plantings and can aid in disturbed site phytoremediation.

- **Conclusion:** As previously reported in scientific literature, some varieties of barley (*Hordeum vulgare* subsp. *vulgare*), a geographically widely-adapted agricultural crop with significant economic potential with the livestock rearing and feeding industry, demonstrated salt tolerance comparable to or better than many indigenous halophytes of the Powder River Basin. Correspondingly, barley has potential to serve as a significant plant species that can serve both beneficial uses for CBM product water and phytoremediation of landscapes impacted by salinity and/or sodicity.

**Screening for salt tolerant forage species – candidate evaluation for soil remediation and of forage production potential when irrigated with CBM product water.** A series of prospective greenhouse and field experiments was completed, both on the Montana State University campus and at selected field site locations within the Powder River Basin, to: 1) identify salt tolerant (livestock) forage species; and 2) determine production potential of selected candidates when irrigated solely with CBM product water. The purpose of initial greenhouse experiments was to determine the survivability and early plant biomass production of sixteen forage species irrigated with water qualities chosen to represent surface water supplies that could result from coal bed methane (CBM) development. The water qualities represented water comparable to Powder River water during the irrigation season, CBM product water in Montana

and the Gillette area in Wyoming, and saline-sodic water of coal aquifers in the Tongue River watershed. The overriding objective of this screening was to define a short list of species to be used in long-term field and rainout shelter greenhouse experiments to assess biomass production potential utilizing CBM x surface water mixes.

Initial greenhouse experiments evaluating seedling emergence and survival responses to salinity and sodicity resulted in reduction of an initial list of 16 possible candidate species to a short list of seven species. Those species included the following: tall fescue (*Festuca arundinacea*), intermediate wheatgrass (*Agropyron intermedium*), slender wheatgrass (*Agropyron trachycaulum*), Altai Basin rye (*Elymus angustus*), sorghum (*Bicolor (L.) moench*), corn (*Zea mays*), barley( var. Valier forage) (*Hordeum valier*), tall wheatgrass (*Agropyron elongatum*).

Subsequent to the seedling screening and field trails, a short list of eight forage species that performed well in long-term experiments to assess forage biomass production in modestly saline x sodic water conditions was developed. That list is essentially the same as the screening list, excluding sorghum (*Bicolor (L.) moench*), corn (*Zea mays*), tall wheatgrass (*Agropyron elongatum*). In addition, three specific ‘hay’ barley varieties were identified and included in the list. Those varieties were Valier, Haybet, and Haxby.

In addition, halophytes suitable to wet areas and ephemeral channels were identified through performance evaluation. The following species were identified as suitable candidates for ephemeral channel vegetation, channel stabilization, channel restoration in areas where CMB product water might be discharged: Baltic rush, American bulrush, Inland salt grass, Alkali grass, Foxtail barley (maritime), Prairie cordgrass and alkali cordgrass, and cattail.

### **Commercial Treatment of CBM Product Water for Beneficial Uses**

**Commercial-scale system design and proto-type development of treatment processes for reduction of salinity and sodicity concentrations of CBM product water.** A 30-month subcontract was issued to Drake Water Technologies, Helena, MT for the design, proto-type development and commercial scale-up of water treatment technology for the reduction of salinity and sodicity (SAR) of CBM product water. As proposed by the subcontractor, design, development, testing, and patenting of an onsite, mobile water treatment plant specific to the signature of PRB CBNG produced water (details are available at <http://waterquality.montana.edu/docs/methane/cbm-wts.shtml>) was completed. The Drake Process utilizes a novel, continuous fluid-bed ion exchange process to treat CBM water generated during natural gas production. Sodium bicarbonate is removed from the saline produced water to reliably yield fresh water that meets the most stringent regulatory water quality parameters. Upon subcontract completion, Drake Water Technologies secured US. Patent No. 7,368,059-B2, “Method for removal of benevolent cations from contaminated water”. A “beta” Drake Process Unit (DPU) was subsequently deployed and operated at a Willow Creek, WY CBM development site, within the Powder River Basin, south of Gillette, WY. Sodium removal was 84% with a discharge pH of 7.4

- **Conclusion:** Commercial-scale CBM product water treatment technologies are currently available and operational within the Powder River Basin. These technologies are capable of reducing sodium and salinity concentrations of CBM product water to levels compatible with currently permitted in-stream and discharge standards established by the Montana Department of Environmental Quality.

## **Landscape x Coalbed Methane Product Water Interactions**

**Soil water retention at varying matric potentials following repeated wetting with modestly saline-sodic water and subsequent air drying.** A prospective, laboratory study was completed examining the effects of surface irrigation with simulated CBM product water on soil physical property alteration and soil water retention. The underlying objective of this study was to determine the degree, if any, to which agricultural land (namely soil resources) would be adversely impacted by CBM product water. Under laboratory conditions, selected soils from the Powder River Basin were subjected to various simulated irrigation scenarios and subsequent drying, followed by leaching with salt-free water. This latter step was completed to simulate ‘pure’ water rainfall additions following wetting of soil with saline-sodic water. Treated samples were then re-saturated with the final treatment water and equilibrated to -10, -33, -100, -500, or -1,500 kPa. Subsequently, the capacity of each soil to retain water was determined.

- **Conclusion:** At all potentials (equilibration pressures), soil water retention increased significantly with increasing clay content. Drought prone soils lost water holding capacity between saturation and field capacity with repeated wetting and drying, while finer textured soils withstood this treatment better and had increased water retention capacity at lower matric potentials. While soil water retention on a mass basis differed significantly among all textural groups at each matric potential studied, greatest differences occurred at -10, -33, and -100 kPa, indicating that effects of texture on soil water retention decrease with decreasing (drier) matric potentials.
- **Conclusion:** soil composition more dramatically influences water retention Under normal moisture management conditions (i.e. 0 to -100 kPa, comparable to what might be encountered under crop growing conditions) than under extremely dry conditions. This alteration, which translates to an increase in soil water retention, likely resulted from an increase in micropores following wetting with low EC water.
- **Conclusion:** In terms of management of sodic irrigation water, producers must be aware that coarse textured soils (those typically considered generally ideal for irrigation are more susceptible to structural losses at high matric potentials (wet conditions) as a result of repeated wetting and drying than fine textured soils. Essentially, soils already prone to drought because of textural characteristics lose water holding capacity and become even drier at high matric potentials with repeated wetting and drying, while finer textured soils have a greater ability to withstand such treatment. Because these losses occur at high

matric potentials in coarse textured soils, they more greatly impact production than losses seen at low potentials in fine textured soils.

A second phase of this controlled laboratory experiment assessed acute and chronic soil solution salinity and sodium-induced soil dispersion indices responses to various wetting regimes simulating repeated flood irrigation with treated CBM product water, followed by single rainfall events. (Note: electrical conductivity (EC) of soil solution is typically used as a surrogate measure of solution salinity; sodium adsorption ratio (SAR) of soil solution is typically used as a surrogate measure of soil dispersion tendency.) Fifty-four representative soil materials from irrigated fields in southeast Montana were subjected to various wetting regimes with simulated CBM product water. Repeated wetting with PR water having EC of  $1.56 \text{ dS m}^{-1}$  and SAR of 4.54 led to SAR  $<12$ , but brought ECe near  $3 \text{ dS m}^{-1}$ . Repeated wetting with water having salinity =  $3.12 \text{ dS m}^{-1}$  and SAR = 13.09 led to ECe  $>3 \text{ dS m}^{-1}$  and SAR near 12. Subsequent inundation and drainage with simulated rainfall-quality leaching, reduced ECe and SAR more often in coarse-textured, high salt content soils than in finer-textured, lower salt content soils. Decreases in ECe upon leaching with distilled water were of greater magnitude than corresponding decreases in SAR, reinforcing supposition of sodium-induced dispersion of fine-textured soils as a consequence of rainfall following irrigation with water having salinity and sodicity levels equal to previously published thresholds.

- **Conclusion:** Study results confirmed previously published relationships between applied water salinity (EC) and sodium adsorption ratio (SAR) and resultant soil solution ECe and SAR. Repeated wetting and drying events caused ECe to equilibrate at approximately 2–3 times irrigation water EC.
- **Conclusion:** Under conditions of this study, post-irrigation (simulated) SAR roughly approximated SAR of the applied water. SAR values following all treatments were approximately related to ESP by the equation  $\text{SAR} = 0.80 \times \text{ESP}$ , reported by the U.S. Salinity Laboratory in 1954. (Note: ESP = exchangeable sodium percentage.)
- **Conclusion:** Reliable empirical models appear to be valid for estimating soil and soil solution responses, with respect to salinity and sodicity, to CBM product water dispersed to landscape or applied as irrigation water. Correspondingly, land and water managers working under similar conditions with CBM product water can use applied water SAR to approximate resultant soil ESP and SAR. In terms of salinity, single or infrequent applications of modest amounts of CBM product water posed little risk of causing sodium-dominated smectitic soil to become saline, as defined by a salinity threshold.

**Soil water flow and irrigated soil water balance in response to Powder River Basin coalbed methane product water.** A prospective laboratory experiment, consisting of packed soil columns, was completed to obtain input data for a series of computer soil water balance simulations assessing potential impacts of CBM product water from the Powder River Basin (PRB) on soil water flow and water balance in Powder River Basin soils. A and B horizon



materials from sandy loam, silt loam, and clay loam soils were pre-treated with water having salinity and sodicity typical of CBM product water. Under pre-treatment water testing, sandy loam and clay loam soils pre-treated with CBM water exhibited smaller infiltration flux values than when pre-treated with irrigation water sourced from perennial streams within the Basin. Only sandy loam soil showed a significant decrease in infiltration flux with simulated rainfall on soils pre-treated with CBM, when infiltration fluxes were compared to those of the same soils initially wetted with simulated river water.

The soil water balance numerical simulations modeled potential effects of sodic irrigation waters on sandy loam, silt loam, clay loam and silty clay PRB soils under sprinkler or flood irrigation, during one growing season. Baseline soil water retention functions were constructed for five soil materials, and adjusted via trends identified in the literature to create five additional functions for each soil, simulating exposure to five increasingly sodic irrigation waters. The simulations did not include salt transport or salinity balance, and therefore did not address total salinity or specific ion effects on plant water uptake or physiology. Rather, they were intended to provide insight concerning potential impacts of changes in soil hydraulic properties only on the partitioning of water balance components during a single growing season. Inclusion of salt transport and salinity impacts on these processes requires substantially more knowledge of soil properties than was available and incurs additional model uncertainty beyond that involved in soil water flow. Simulation results showed greater impact of sodic irrigation under flood than sprinkler irrigation. Fine sandy loam and silty clay loam soils exhibited the fewest changes in water balance partitioning, while silt loam and silty clay soils showed the greatest changes, especially in increased runoff and reduced transpiration.

The water balance of coarser soils was less affected by altered hydraulic properties than was that of finer soils, although silty clay loam soil exhibited smaller changes than did more finely textured silt loam soil because of the specific imposed modifications to the soil hydraulic properties. Fine sandy loam appeared to maintain conditions favorable to root water uptake and deep drainage, whereas silt loam soil appeared to reach a threshold at the 4<sup>th</sup> level of simulated sodicity, at which there were decreases in root water uptake under both irrigation methods, and increases in runoff with sprinkler irrigation. In this soil under sprinkler irrigation, decreased root water uptake was a result of slow drainage and therefore lack of aeration due to high wetness, while under flood irrigation, the decline in transpiration was likely attributable to decreases in surface infiltration and in plant-available water. Relatively high surface runoff and low infiltration values characterized the finest-textured silty clay soil.

- **Conclusion:** Soil baseline chemistry and level of aggregation should be taken into account, in addition to texture and clay content, when use of CBM product water for irrigation is considered.
- **Conclusion:** Simulation results suggest that PRB landowners contemplating the use of CBM product water for irrigation may wish to consider that clay content and soil texture may not be proportionally related to susceptibility to adverse effects of sodic water, and that a lower-intensity, higher-frequency irrigation method such as sprinklers may allow

soils to maintain hydraulic function more readily than less frequent, high-water-volume flood irrigations.

- **Conclusion:** Enhancement of infiltration during flood irrigation of fields with CBM product water may be accomplished by allowing water to remain ponded for longer periods, as long as soil aeration does not decline below critical levels.
- **Conclusion:** Based on both the experimental and computer simulation investigations, it appears that PRB CBM water might be productively used for irrigation under some conditions without adverse effects on soil water flow or on the partitioning of water in soils. Prudent use would involve not only examination of soil texture and clay fraction and of irrigation water salinity and sodicity, but also monitoring of soil salt balance, and application of water at a rate compatible with the soil's capacity for infiltration and hydraulic conductivity.

**Response of grass species to soil salt content and cover soil depth on lands developed for coalbed methane.** Two prospective greenhouse studies were completed to evaluate the emergence and growth of three native grass species (bluebunch wheatgrass, *Pseudoroegneria spicata* (Pursh) A. Love); (needle and thread, *Hesperostipa comata* (Trin. & Rupr.) Barkworth); and (western wheatgrass, *Pascopyrum smithii* (Rydb.) A. Love)), as a function of i) soil salt content and matric potential, and ii) coversoil depth overlying a saline substrate. These studies were initiated in the interest of defining reclamation and mitigation measures that may be necessary in association with land-applied CBM-product water or site disturbance related to CBM-product water impoundment construction. Seedling emergence, plant height, above-ground biomass, and below-ground biomass were significantly decreased by increasing soil salinity of resident soil and by decreasing soil moisture available to germinating and emerging seedlings. These results were consistent with previously reported results from similar studies. A correlation analysis showed matric potential, i.e., how wet or dry the soil was at the time of emergence, to be more significantly correlated to seedling emergence and growth than soil salinity. This effect of reduction of growth due to 'soil drying' was compounded by increasing salinity of the resident soil. Conversely, emergence for plants grown in elevated salinity increased as much as 26.7 % when moisture was high. At low soil moisture, elevated salinity resulted in emergence losses as high as 88.3 %. Losses in aboveground biomass ranged from 23.0 to 97.9 % at moderate salinity and 27.3 to 98.5% at high salinity.

For the second study, a revegetation substrate consisting of a mixture of soil and geologic stratum, was initially salinized to an EC of 11.0 dS/m. This material was designed to represent a salinized subsoil, over which stock-piled, non-saline cover soil was applied, as a measure of reclamation or mitigation of CBM product-water impoundment sites or agricultural areas previously salinized by surface-applied CBM product water. Non-saline coversoil was applied on top of the saline substrate at thicknesses of 0, 5, 10, 15, 30 and 45 centimeters. Above-ground and below-ground biomasses were significantly greater with increased coversoil depth, with depths of 15, 30 and 45 cm producing similar results.

- **Conclusion:** Impacts of elevated soil salinity, due either to salinization due to CBM product water impoundment, evaporation of surface-applied CBM product water, or exposure of salt-burdened subsoils during site excavation or soil mixing, are highly influenced by soil moisture. Irrigation will be an important factor in revegetation of saline soils. Also, investigators studying plant growth on saline soils must closely consider the impact of soil moisture on study results.
- **Conclusion:** In areas where land is disturbed to extract energy resources, such as CBM, improper soil management on drill pads, constructed and/or abandoned product water impoundment sites, or salinized landscapes due to surface-applied CBM product water, may result in soil impaired by elevated salinity. Results suggest that coversoil is necessary to improve plant growth on a saline substrate, but applications of less than 45 cm may be adequate.
- **Conclusion:** Soil moisture plays an integral role when evaluating the negative impacts of elevated soil salinity on rangeland vegetation establishment and early growth. Results may be easily biased through the consideration or assumption of only one moisture regime, or by not thoroughly elucidating the moisture regime used in the revegetation effort. Additionally, the designation of specific threshold levels for salt tolerance may be of limited value. It is crucial that investigators studying plant responses to soil salinity consider the importance of soil moisture.

#### **Characterizing infiltration related to coalbed methane impoundments in the upper Hanging Woman drainage of Wyoming.**

A multi-phase approach was taken to assess potential seepage rates from CBM product water storage ponds in the Upper Hanging Woman drainage. The project initially involved making an initial assessment of lands on a privately-owned ranch in the Upper Hanging Woman drainage, in terms of expected differences in the degree of seepage below CBM impoundments and the likely final destination of product water leaving the ponds. Three landscape classes were used in the subsequent analysis: bedrock controlled hillslopes with shallow sedimentary beds, alluvial fine-loamy soils, and alluvial fine family soils. A total of nine study sites were selected in the field, three from each landscape class. Phase two of the project was to run rapid infiltration tests similar to a perk test at each of the sample site locations. These were intended to provide a screening tool for assessing spatial variability at each site relative to hydraulic properties. They also provide an integrated measure of infiltration at each site without assessing the hydraulic properties of specific layers. Twenty-two measurements of saturated hydraulic conductivity in variable soil and substrate materials and associated infiltration tests were completed to assess how much water will seep out of a specific CBM pond.

Basic patterns of infiltration were consistent within each class for the majority of profiles tested. Spatial variability was least in the fine family soils, slightly higher in fine-loamy soils and substantially greater in the sedimentary beds. Infiltration in the sedimentary beds exhibited a

high degree of spatial variability in the infiltration tests run. The highest infiltration rates measured occurred in sedimentary beds as well as some of the lowest. Averaged across all sites, the overall infiltration rate for sedimentary beds was higher than fine-loamy or fine family soils examined in this study. Deep alluvial soils in general have heavy soil textures that result in naturally slow infiltration. Results of field measurements of infiltration on selected pond sites revealed that pond seepage in mixed sedimentary landscapes does occur with substantial magnitude. Downward flow of water through mixed sedimentary beds is likely based on the data collected and once water has left the pond, lateral flow is inevitable given the abrupt changes in saturated hydraulic conductivity with depth in mixed sedimentary materials.

- **Conclusion:** USDA countywide soil surveys when used inappropriately to determine site specific soil properties are often inaccurate. Inaccuracy increases as the complexity of the landscape increases. The soil surveys do provide good information about general soil properties and how they are spatially distributed over large areas. Thus, use of the soil survey for making interpolations on a small scale, i.e.: large area, basis is an appropriate use of the information available.
- **Conclusion:** Soil-landscape units appear to provide the right level of resolution and the proper scale to model spatially distributed functions such as pond seepage potential or infiltration rates across landscapes.
- **Conclusion:** Likelihood of pond seepage is relatively high and predictable when unlined impoundments are placed within or intersecting mixed sedimentary beds with sediment-derived landscapes. Downward flow of water through mixed sedimentary beds is a function of geomorphic configuration; once water has seeped from impounded areas in the sedimentary landscapes, lateral flow is inevitable given the abrupt changes in saturated hydraulic conductivity with depth in mixed sedimentary materials.

**Assessment of effect of coalbed methane product water intervention on water quality parameters in the Little Powder River at Weston, Wyoming.** A detailed time time-series analyses of selected datasets of public record of waters of the Little Powder River, a tributary to the Powder River, originating in Wyomin, was completed. The objective was to assess by comparative analyses impacts of CBM product water management and discharges in a relatively small basin on down-gradient stream quality characteristics. A suite of statistical analyses and data transformations were completed to determine if trend analyses, time series and intervention analyses could identify and/or quantify significant changes in Little Powder River sodium concentration and sodium adsorption ratio (SAR), and which might be coincident with coalbed methane product water reaching the main channel of the Little Powder River. The investigation initially focused on Rosebud Creek and Hanging Woman Creek (in Montana), Prairie Dog Creek and Badger Creek (in Wyoming), the Tongue River in Montana and Wyoming, its tributaries (in Wyoming), and the mainstem of the Powder River above and below the confluence with the Little Powder River. Various parametric and non-parametric statistical analyses were conducted on a time series of existing U.S. Geological Survey data for the Little Powder River above Dry

Creek confluence, near Weston, WY (USGS site 06324970). Existing data were partitioned into two defined periods, relative to significant CBM development, i.e., pre-development period (1976-1981) and post (initiation of development, 1999-2002). These two periods were selected because of the equality of size of data sets, the comparatively equal climatic and flow conditions, and the lack of compromising circumstances during either of the selected periods.

Initial assessment of publicly available records specific to flow and water chemistry for the Tongue River, Prairie Dog Creek, Badger Creek, Hanging Woman Creek, Rosebud Creek, the mainstem of the Powder River above the confluence with the Little Powder River, indicated that existing databases of all investigated flows (with the exception of the Little Powder River near Weston, WY) were inadequate, incomplete or compromised by pre-existing conditions sufficiently to preclude developing conclusions or completing time series analyses and assessments that would result in any significant degree of confidence with respect to outcomes of the analyses.

- **Conclusion:** Parametric analyses of sodium concentration, sodium adsorption ratio, and specific conductance of flows of record of the Little Powder River, when flow-adjusted, indicated elevated (but not highly significant) sodium concentration, SAR, and specific conductance between the pre-development period dataset (1976-1981) and the post-development period (1999-2002). Substantial increases in average sodium concentration and average specific conductance occurred during the months of May through December during the post-development period; SAR increases occurred in April through December during the post-development period (1999-2002). Non-parametric analyses were less conclusive. Based on the varied results from the time-series assessment of records of the Little Powder River above Dry Creek, near Weston, WY, although it appears likely, it is difficult to conclude whether or not coalbed methane product water is reaching the Little Powder River and thereby altering the chemistry of this tributary to the Powder River.
- **Conclusion:** The lack of adequate baseline data, the incompleteness of data sets associated with the water bodies investigated, and the compromising situations encountered on some of the water bodies is particularly important from the perspective of both short-term and long-term assessments of large-scale, hydrologic or watershed based implications or interactions of large-scale CBM product water discharges, releases, or escapes (infiltration, leaching) from impoundment storage facilities. This situation of inadequate, incomplete, or compromised databases leaves developers and entities responsible for permitting and regulating CBM product water management vulnerable to inability to complete accurate present-time assessments, forward projections of long-term impacts on downstream receiving water bodies, or make numerically based decisions regarding basin-wide water management decision implications and interactions (and potentially subject to future assignment of liability and litigation).

**Beneficial use of CBM product water to enhance terrestrial carbon sequestration in wetland settings.** A prospective greenhouse study was completed to evaluate the potential for use of CBM production water to facilitate terrestrial carbon sequestration in the form of increases

in sustainable soil organic matter (SOM), or geologic carbon sequestration in the form of calcium carbonate ( $\text{CaCO}_3$ ) precipitation in the soil. Plant species targeted was American bulrush (*Schoenoplectus americanus*), which was planted in controlled soil columns and managed under continuous CBNG product water irrigation for approximately 24 months. Soil total carbon (%) and  $\text{CaCO}_3$  (%) levels increased during the two-year study. Increases were similar in columns irrigated with either CBM or non-CBM product water. No correlation to water chemistry could be determined, substantiating that: 1) availability of additional water in water-limited environments such as the Powder River basin can facilitate some short-term carbon accumulation, and 2) species such as American bulrush appear to be generally insensitive to either CBM product water quality or resulting near-saturated soil conditions under sustained irrigation and/or flooding. Likewise, soil carbon increases could not be correlated to increases in  $\text{CaCO}_3$ . Recent literature suggests sampling to depths below 10 cm may result in a better total carbon budget in irrigated soils (Eshel et al., 2007). Literature also suggests carbon sequestration takes longer than 2 years, some estimates suggest 5-10 years, so continuing the project for more than two irrigation seasons may illustrate some trend in increase in soil carbon and  $\text{CaCO}_3$  levels.

- **Conclusion:** Short-term terrestrial carbon sequestration enhancement with CBM product water appears to have limited potential at present with the currently understood plant species.

## Conclusions

- **Phytoremediation, i.e., functional use of plants, to reduce sodium concentrations in CBM product water is not a sustainable or effective short-term or long-term management option within the Powder River Basin.**
- **Phytoremediation, using selected livestock forage species, as a means of reclamation of salt and sodium-affected soils is a viable long-term management consideration in those circumstances where land-application of saline or sodium-rich water has ceased and forage removal by grazing and/or harvesting is adopted as a long-term vegetation management strategy.**
- **Industrial-scale water treatment facilities are available and functional for the reduction of salinity and sodicity within CBM product water prior to discharge or land application.**
- **Long-term irrigation with CBM product water of the quality commonly occurring in the Powder River Basin poses the potential of elevated salinity levels within shallow alluvial groundwater, alterations in soil physical and chemical properties on selected soils, ultimately requiring remediation intervention.**
- **Selected native and introduced livestock forage plants are well-adapted to functional performance (survival, growth, reproduction) in circumstances where CBM product water is either the sole or principal water source. Functional performance might include forage production, wildlife habitat, stream channel stabilization, saline-affected site reclamation/remediation.**
- **Currently promoted practices of treating CBM produced water to EC and SAR levels published by Richards et al. (1954) and subsequent use as irrigation water on smectite-dominated soils may lead to soil solution E<sub>C</sub>e and SAR combinations contributing to sodium-induced dispersion. This is especially the case following rainfall events of sufficient amount on Na-dominated smectitic soils to induce soluble salt leaching from the upper parts of the soil profile.**

## **Appendix – Publications, thesis, patents, technical reports produced with funding provided through this award**

### **Scientific Journal (peer reviewed) Publications:**

Bauder, J. W. and T. A. Brock. 2001. Irrigation water quality, soil amendment, and crop effects on sodium leaching. *Arid Land Research and Management* 15:101-113.

Keith, K., H. Sessoms, M. Neibauer, Q. Skinner, J. Bauder, R. Waskom, and N. Mesner. 2005. Land and water inventory guide for landowners in areas of coal bed methane development. 1<sup>st</sup> Edition. *Montana State University Extension Service*, EB166. 77 pg.

Browning, L.S., K. R. Hershberger, and J. W. Bauder, 2007. Soil water retention at varying matric potentials following repeated wetting with modestly saline-sodic water and subsequent air drying. *Comm. Soil Sci., and Plant Anal.* 38:1-16.

Bauder, J. W., K. R. Hershberger, and L. S. Browning. 2008. Soil solution and exchange complex response to repeated wetting-drying with modestly saline-sodic water. *Irrigation Sci.* 26:121-130.

Browning, L. S., J. W. Bauder, and S. D. Phelps. 2006. Effect of irrigation water salinity and sodicity and water table position on water table chemistry beneath *Atriplex lentiformis* and *Hordeum marinum*. *Arid Land Research and Management*. 20: 1-15.

Bauder, J. W. and T. A. Brock. 2001. Irrigation water quality, soil amendment, and crop effects on sodium leaching. *Arid Land Research and Management* 15:101-113.

Bauder, J. W., L. S. Browning, S. D. Phelps, and A. D. Kirkpatrick. 2008. Biomass production, forage quality, and cation uptake of Quail bush, 4-wing saltbush, and seaside barley irrigated with moderately saline-sodic water. *Communications in Soil Science and Plant Analysis*.

### **Graduate Thesis Published:**

Garver, Keri M., 2004. Assessment of effect of coalbed methane product water intervention on water quality parameters in the Little Powder River at Weston, Wyoming. M.S. thesis. Land Resources and Environmental Sciences, Montana State University, Bozeman. 144 p.

Kirkpatrick, A. 2005. Assessing constructed wetlands as a management option for beneficial use of saline-sodic product water. M.S. Thesis, Land Resources and Environmental Sciences. Montana State University., Bozeman. 79 p.



Sessoms, Holly., 2004. Water use potential and salt tolerance of riparian species in saline-sodic environments. M.S. thesis. Land Resources and Environmental Sciences, Montana State University., Bozeman. 73 p.

Robinson (Hershberger), K. 2003. Effects of Saline-Sodic Water on EC, SAR, and Water Retention. M.S. thesis. Land Resources and Environmental Sciences, Montana State University., Bozeman. 172 p.

Phelps, Shannon D., 2003. Effect of Irrigation Water Quality and Water Table Position on Ploant Biomass Production, Crude Protein, and Base Cation Removal. M.S. thesis. Land Resources and Environmental Sciences, Montana State University., Bozeman. 188 p.

Buchanan, Margaret MaacNeill, 2005. Soil water flow and irrigated soil water balance in response to Powder River Basin coalbed methane product water. Montana State University, Department of Land Resources and Environmental Sciences. M.S. Thesis. 151 pp.

Mitchem, Melissa Deanne. 2005. Response of grass species to soil salt content and coversoil depth on lands developed for coalbed methane. Montana State University, Department of Land Resources and Environmental Sciences. M.S. Thesis. 210 pp.

#### **Scientific literature reviews and summaries published:**

A General Essay on the Bioremediation of Contaminated Soil (2006) This paper summarizes the general processes of bioremediation within the soil environment, focusing on biodegradation of petroleum hydrocarbons. The effect of soil conditions on rate of biodegradation of hydrocarbons is addressed. Further, limitations and potential of both *ex situ* and *in situ* bioremediation as viable alternatives to conventional remediation are explained and addressed.

<http://waterquality.montana.edu/docs/methane/Donlan.shtml>

Coal Bed Methane Ownership and Responsibility: A Summary of Surface, Mineral, and Split-Estate Rights (2001) This review defines and explains the major components of historical surface, mineral, and split-estate resource ownership law in the United States, concentrating on the Amoco Production Co. v. Southern Ute Indian Tribe Supreme Court decision declaring an opinion of the U.S. congressional intent in the creation of the Coal Lands Acts of 1909 and 1910.

<http://waterquality.montana.edu/docs/methane/splitestate.shtml>

Quality and Characteristics of Saline and Sodic Water Affect Irrigation Suitability (2002) Two possible management options for the beneficial use of coal bed methane water are sprinkler irrigation and land spreading. Certain criteria and careful management strategies need to be met to achieve sustainable soil quality and plant production using saline-sodic water.

[http://waterquality.montana.edu/docs/methane/irrigation\\_suitability.shtml](http://waterquality.montana.edu/docs/methane/irrigation_suitability.shtml)

Justification for Numeric Standards of Salinity and Sodicity of Water To Be Considered For Beneficial Use For Irrigation (2002) This paper addresses the general issue of narrative and

numeric surface water quality standards and the controversy over the value, appropriateness, and specific numeric and narrative standards specific to salinity and sodicity of waters to be considered for either irrigation or land spreading in the Powder River Basin.

<http://waterquality.montana.edu/docs/methane/standards.shtml>

The Role of Plants in Bioremediation of Coal Bed Methane Product Water (2001) Halophytes are defined as salt tolerant plants that can uptake excess salts and potentially remediate the saline-sodic conditions associated with coal bed methane product water.

<http://waterquality.montana.edu/docs/methane/halophytes.shtml>

The Use of Coal Bed Methane Product Water to Enhance Wetland Function (2003) A possible strategy to aid in processing coal bed methane product water is to construct wetlands composed of a variety of halophytic plants which have dense fibrous root systems, uptake salts and sodium, can be used as forage, have high ET and water use rates, or have a combination of these traits.

<http://waterquality.montana.edu/docs/methane/wetlandenhancement.shtml>

#### **Poster presentations/Posters:**

From Prehistory to the Pipeline - The Fingerprint of Coal Bed Methane (2004) Information about the formation and production of biogenic and thermogenic methane, global estimates of coal bed methane production, and estimates of coal bed methane production in the Rocky Mountain west. Presented by Suzanna R. Roffe (Montana State University) at the 2004 Montana Soil and Water Conservation Society Annual Meeting in Billings, Montana.

[http://waterquality.montana.edu/docs/methane/roffe\\_swcs.pdf](http://waterquality.montana.edu/docs/methane/roffe_swcs.pdf)

Applied Science for the Beneficial Use of Saline-Sodic Water (2003) Coal bed methane product water management and beneficial use options. Overview of the Montana State University coal bed methane research goals, completed projects and emerging research. Presented by Krista E. Pearson (Montana State University) at the 2003 ASA-CSSA-SSSA Annual Meetings in Denver, Colorado. <http://waterquality.montana.edu/docs/methane/appliedscience.pdf>

Geochemical Constraints on Selection of CBM Product Water Management Strategies (2004) Understanding the fundamental chemical behavior of coal bed methane product water is key to designing and implementing successful water management strategies. Presented by Ron Drake (Drake Engineering Incorporated) at the 2004 Montana Soil and Water Conservation Society Annual Meeting in Billings, Montana.

[http://waterquality.montana.edu/docs/methane/rdrake\\_swcs.pdf](http://waterquality.montana.edu/docs/methane/rdrake_swcs.pdf)

Selected Plant Species Tolerance for Irrigation with Saline-Sodic Water (2003) To allow extensive use of saline water, a by-product of coal bed methane extraction, controlled greenhouse and field experiments have been used to determine survivability and plant biomass of forage species irrigated with saline water. Presented by Allison Levy (Montana State University) at the 2003 ASA-CSSA-SSSA Annual Meetings in Denver, Colorado.

[http://waterquality.montana.edu/docs/methane/levy\\_poster.pdf](http://waterquality.montana.edu/docs/methane/levy_poster.pdf)

Coordinated Natural Resource Monitoring and Training Program for Landowners with Land Parcels in Areas of Coal Bed Methane Development (2003) Investigates common issues landowners may face following coal bed methane development. To extract methane from a coal seam, networks of wells, pipelines, and roads are placed across the landscape and large volumes of sometimes marginal quality water must be managed. Presented by Kristin Keith (Montana State University) at the 2003 ASA-CSSA-SSSA Annual Meetings in Denver, Colorado. [http://waterquality.montana.edu/docs/methane/keith\\_swcs.pdf](http://waterquality.montana.edu/docs/methane/keith_swcs.pdf)

### **Power Point Presentations:**

Using CBM Product Water for Irrigation (2004) Information on salinity and sodicity issues, irrigation, infiltration, and movement of water in the soil. Presented by Dr. Jim Bauder (Montana State University) at the 2004 Montana Soil and Water Conservation Society Annual Meeting in Billings, Montana. [http://waterquality.montana.edu/docs/methane/bauder\\_swcs.ppt](http://waterquality.montana.edu/docs/methane/bauder_swcs.ppt)

Diagnosing Salinity Problems (2003) The symptoms and causes of salinity, high pH, specific ion toxicity and sodicity are frequently misunderstood. All have adverse affects plant growth, but differ significantly in their cause and relative impact. Proper field and laboratory diagnostics are critical to successful problem correction when dealing with saline and sodic soil and water quality issues. Presented by Dr. Reagan Waskom (Colorado State University) at the 2003 ASA-CSSA-SSSA Annual Meetings in Denver, Colorado. <http://waterquality.montana.edu/docs/methane/waskom.pdf>

Matching Soil, Water, and Crops to Saline and Sodic Conditions (2003) Provides guidelines for irrigation use in determining suitability of saline-sodic irrigation water for specific irrigated soil x crop combinations. Outlines the components of salinity control to encourage sound practices on farms. Presented by Kristin Keith (Montana State University) at the 2003 ASA-CSSA-SSSA Annual Meetings in Denver, Colorado. <http://waterquality.montana.edu/docs/methane/keith.pdf>

Preventing, Correcting, and Managing Salinity and Sodidity (2003) Prevention and correction of salinity and sodicity problems by managing crops and soils through knowledge of leaching controls (ESP, SAR) and reclamation of salinity and sodicity problems. Presented by Dr. J.D. Oster (University of California-Riverside) at the 2003 ASA-CSSA-SSSA Annual Meetings in Denver, Colorado. <http://waterquality.montana.edu/docs/methane/oster.pdf>

Screening for Salt Tolerant Forage Species (2003) The purpose of this experiment was to determine the survivability and early plant biomass production of sixteen different forage species irrigated with water qualities that have been chosen to represent conditions of water surface supplies that could result from coal bed methane development. [http://waterquality.montana.edu/docs/methane/blm-doe\\_levy.ppt](http://waterquality.montana.edu/docs/methane/blm-doe_levy.ppt)

Coal Bed Methane - Background Information (2003) . [http://waterquality.montana.edu/docs/methane/blm-doe\\_bauder.ppt](http://waterquality.montana.edu/docs/methane/blm-doe_bauder.ppt)

Coal Bed Methane Product Water Management and Disposal Economics in the Rocky Mountain Region (2003). [http://waterquality.montana.edu/docs/methane/blm-doe\\_econ.ppt](http://waterquality.montana.edu/docs/methane/blm-doe_econ.ppt)

Effects of Saline-Sodic Water Management on Soil Chemical Properties (2003) The purpose of this project was to determine the compatibility between coal bed methane product water and potentially irrigable soils and the effects product water may have on soil chemical properties when applied to the irrigable soils of southeastern Montana.

[http://waterquality.montana.edu/docs/methane/blm-doe\\_hershberger.ppt](http://waterquality.montana.edu/docs/methane/blm-doe_hershberger.ppt)

A Comparison of Seasonal Evapotranspiration of Three Wetland Plant Communities (2003) The objectives of this research are to measure and compare seasonal evapotranspiration for each plant community, monitor changes in water chemistry and temperature fluctuations, and determine the plant/community biomass production.

[http://waterquality.montana.edu/docs/methane/blm-doe\\_kirkpatrick.ppt](http://waterquality.montana.edu/docs/methane/blm-doe_kirkpatrick.ppt)

Dynamics of Product Water Chemistry. Defining Native Wetland Species Salt Tolerance and Water Use Rates (2003). [http://waterquality.montana.edu/docs/methane/blm-doe\\_sessoms.ppt](http://waterquality.montana.edu/docs/methane/blm-doe_sessoms.ppt).

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## **National Energy Technology Laboratory**

626 Cochrans Mill Road  
P.O. Box 10940  
Pittsburgh, PA 15236-0940

3610 Collins Ferry Road  
P.O. Box 880  
Morgantown, WV 26507-0880

One West Third Street, Suite 1400  
Tulsa, OK 74103-3519

1450 Queen Avenue SW  
Albany, OR 97321-2198

539 Duckering Bldg./UAF Campus  
P.O. Box 750172  
Fairbanks, AK 99775-0172

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