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U.S. FISH & WILDLIFE SERVICE
REGION 6

CONTAMINANTS PROGRAM

Assessment of Contaminants Associated with Coal Bed Methane-Produced Water and Its Suitability for Wetland Creation or Enhancement Projects

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ABSTRACT

Extraction of methane gas from coal seams has become a significant energy source in the Powder River Basin of northeastern Wyoming. In Wyoming, coalbed methane (CBM) gas is extracted by drilling wells into coal seams and removing water to release the gas. Each CBM well produces an average of 10 gallons per minute (gpm) of water and a maximum of 100 gpm. Disposal of CBM produced water is accomplished by direct discharge to surface drainages, and also by a variety of other treatment and disposal methods. Untreated CBM produced water discharged to surface drainages is the primary method of disposal provided that the CBM produced water meets Wyoming water quality standards. Water failing to meet water quality standards cannot legally be discharged into surface drainages and is alternately discharged into closed containment ponds for soil-ground water infiltration and evaporation. In 2000 and 2001, we collected and analyzed water from CBM discharges and receiving waters and sediment and biota from CBM produced water impoundments. In 2002, we collected and analyzed water from CBM closed containment impoundments. All the samples were analyzed for trace elements. The biota included pondweed (*Potamogeton vaginatus*), aquatic invertebrates, fish, and tiger salamanders (*Ambystoma tigrinum*). One CBM produced water discharge exceeded the chronic criterion for iron and several CBM produced water discharges exceeded the acute criterion for copper. Terminal sinks receiving CBM produced water have the potential for the eventual increase in trace element concentrations in water, sediment and wildlife dietary items such as pondweed and aquatic invertebrates. Waterborne copper, iron, lead, and manganese exceeded chronic criteria in several impoundments receiving CBM produced water. Arsenic, cadmium, nickel, and zinc in sediments from a terminal sink receiving CBM produced water exceeded the threshold effects concentrations for sediment-dwelling organisms. Cadmium and chromium in aquatic invertebrates and pondweed, respectively, from terminal sink sites were elevated. Waterborne selenium concentrations in six of the seven closed containment impoundments and all seven associated CBM discharges ranged from 2.2 to 8.4 µg/L, exceeding the 2 µg/L threshold for bioaccumulation in sensitive species of fish and aquatic birds. Closed containment ponds containing high selenium water may present a risk to aquatic birds using these ponds if the ponds provide a dietary route of exposure through submerged aquatic vegetation or aquatic invertebrates. CBM operators, land managers, and landowners should evaluate the disposal options for CBM produced water on a site by site basis to prevent adverse impacts on soils, groundwater, and surface water as well as fish and wildlife and their habitats.

Acknowledgments: *Thanks are extended to Colleen Cunningham and Brad Rogers for assistance with field work as well as the numerous CBM operators and landowners for access to the CBM production sites. Thanks are also extended to George T. Allen, Brian Cain, Brian T. Kelly, John Wegrzyn and Everett Wilson of the U.S. Fish and Wildlife for reviewing the manuscript. This study was funded by the U.S. Fish and Wildlife Service, Environmental Contaminants Program (Project # 00-6-6F43-FC).*

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INTRODUCTION

The extraction of methane gas from coal seams has become a significant energy source in the Powder River Basin (PRB) of Northeastern Wyoming. From 1976 to 1996 1,169 coal bed methane (CBM) wells were drilled in the PRB. In 2001 the PRB had 4,000 CBM wells in production (US BLM 2003). Over 39,000 CBM wells are scheduled to be drilled in the PRB by 2012 (US BLM 2003). Coal seams can contain up to 6 or 7 times more methane gas than conventional natural gas rock formations (U.S. Geological Survey 1997). In Wyoming, CBM gas is extracted by drilling wells into a coal seam and removing water to release the gas (Figure 1).

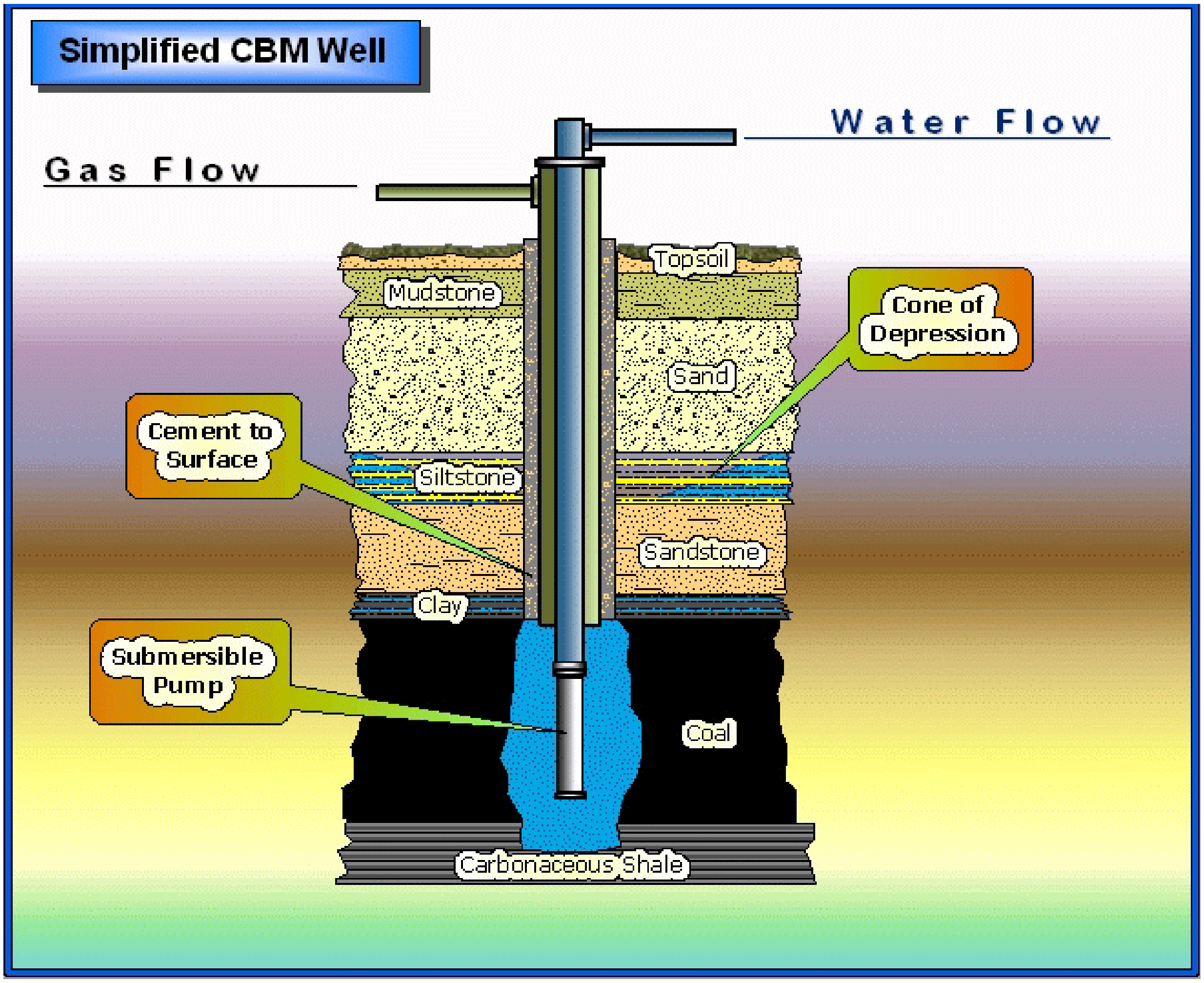


Figure 1. Schematic drawing of a typical coalbed methane well.
(Drawing courtesy of the Coalbed Methane Coordination Coalition, Buffalo, WY.
(http://www.cbmcc.vcn.com/)

CBM wells produce an average of 10 gallons of water per minute (gpm) or 0.02 cubic feet per second (cfs) with a maximum of 100 gpm or 0.2 cfs (US BLM 2003). An annual average of 28,014 acre-feet of CBM produced water is expected to be discharged in the PRB from 2002 to 2017 (US BLM 2003). CBM produced water is disposed of by direct discharge to surface drainages, passive treatment prior to surface discharge, discharge to upland and bottomland infiltration impoundments, discharge to containment impoundments, and deep well injection. Untreated discharge to surface drainages is the primary method of disposal provided that the CBM produced water meets Wyoming water quality standards. Each CBM produced water discharge receives water from five wells. Currently, approximately 3,800 CBM produced water discharge outfalls are permitted by the Wyoming Department of Environmental Quality (WDEQ) through the National Pollutant Discharge Elimination System (NPDES) (Figure 2). Water that does not meet water quality standards cannot be discharged into surface drainages and is usually discharged into closed containment ponds for infiltration and evaporation. NPDES permitees are required to monitor CBM produced water permitted discharges for total petroleum hydrocarbons, specific conductance and pH every 6 months. Radium-226, total iron, total manganese, total barium, and chloride are monitored annually.

Some private landowners use CBM produced water to maintain adequate water levels in stock ponds (Bureau of Land Management 1997). The Fish and Wildlife Service (FWS) Partners for Wildlife Program, Bureau of Land Management (BLM), U.S. Forest Service (USFS), and the Wyoming Game and Fish Department (WGFD) are interested in using CBM produced water for wetland creation and enhancement. An assessment of contaminant risks and impacts from CBM produced water is necessary to assist land managers with the planning of these wetland projects. We conducted this study from 2000 to 2002 to identify contaminant risks to aquatic organisms and aquatic migratory birds from the creation/enhancement of wetlands with CBM produced water.

Table 1 lists trace elements detected in coal seams considered for CBM gas development and shows waterborne selenium in groundwater associated with coal seams ranged up to 31 µg/L. Additionally, application of CBM produced water on soils derived from marine Cretaceous shales can mobilize selenium present in the soil. Selenium contamination and subsequent bioaccumulation in fish and wildlife is likely to occur in areas with: selenium sources, such as seleniferous soils or underlying geologic formations; high evaporation rates (> 2.5 x the precipitation rate); and topographically closed drainage basins, such as closed containment reservoirs or playas used for wastewater disposal (Seiler 1995). Marine Cretaceous shales occur primarily in the eastern and western boundaries of the PRB (Figure 3).

The WDEQ aquatic life chronic criterion of 5 µg/L (parts per billion) selenium is not adequate for preventing adverse effects on fish and aquatic birds. Several scientific experts on selenium have recommended a 2 µg/L criterion because concentrations exceeding 2 µg/L may create a bioaccumulation risk for fish and sensitive species of aquatic birds (Hamilton 2002, Skorupa and Ohlendorf 1991; Lemly 1993). Discharge of produced water containing selenium greater than 2 µg/L also can result in impacts to fish and aquatic birds inhabiting downstream receiving waters.

Table 1. Trace Element Concentrations in Groundwater From Powder River Basin Coal (U.S. Geological Survey 1986).

Element	# of Samples	Median (µg/L)	Maximum (µg/L)	Aquatic Chronic Criteria (µg/L)
As	154	1	120	190
Ba	95	100	1,100	
Cd	165	2	17	1.1
Cr	116	10	50	CrIII = 210, CrVI = 11
Cu	123	100	104	12
Fe	366	100	120,000	1,000
Pb	165	2	180	3.2
Mn	257	40	4,800	
Hg	122	0.4	1.5	0.012
Se	159	1	31	5
Zn	141	20	1,800	110

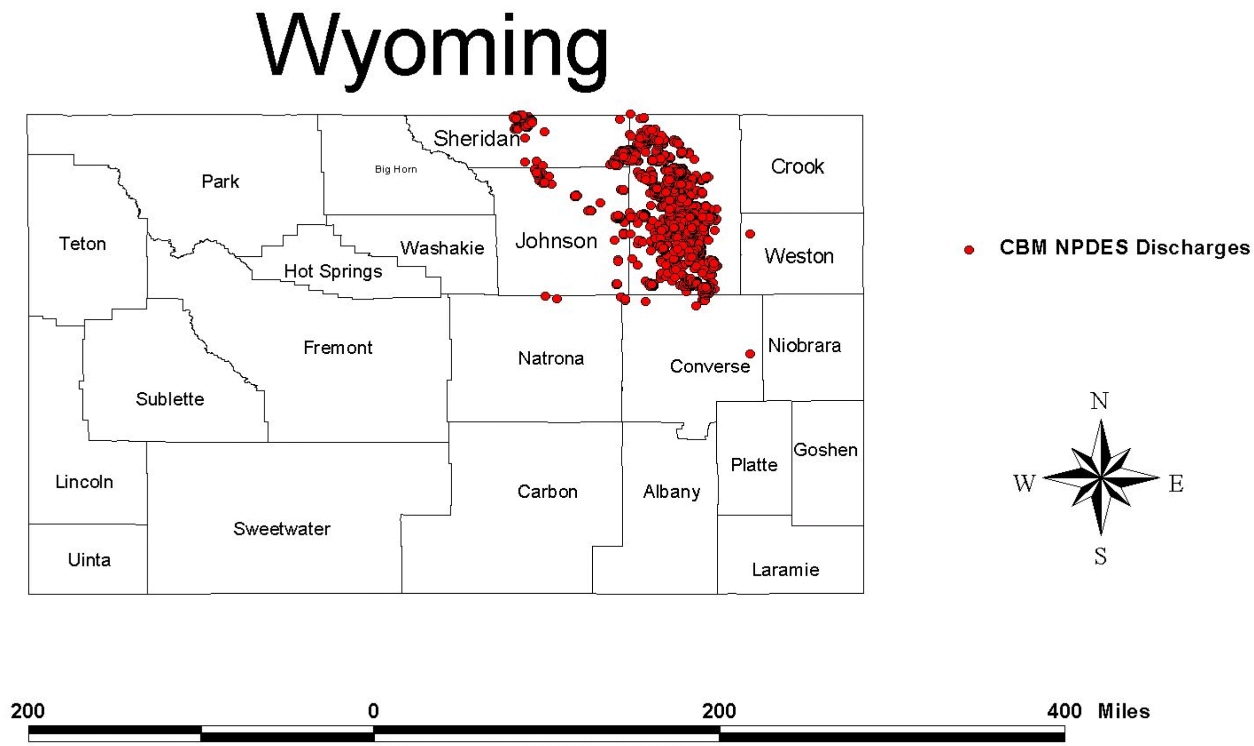


Figure 2. Coalbed methane produced water discharges in the Powder River Basin, Wyoming.

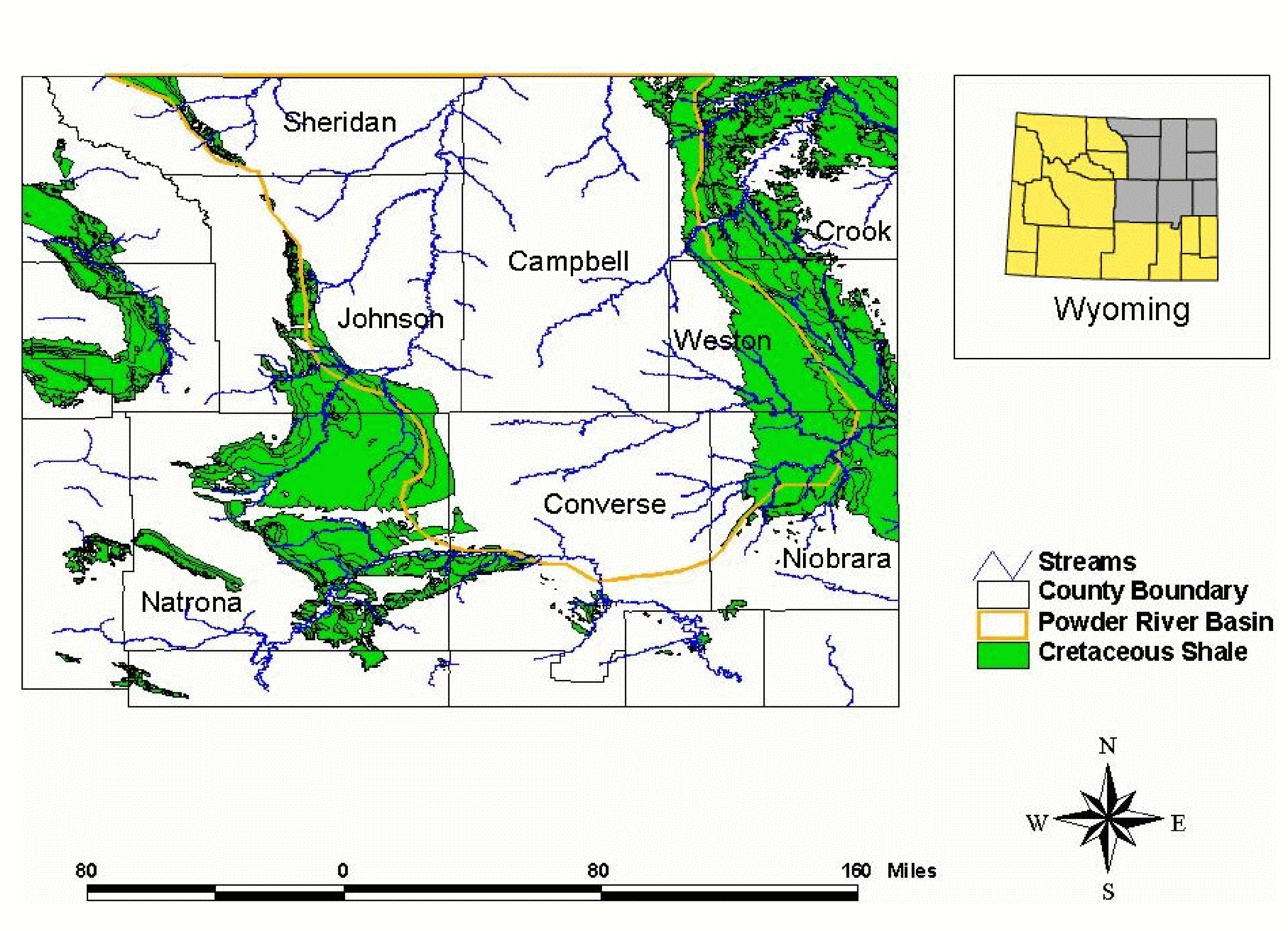


Figure 3. Marine Cretaceous shale formations within the Powder River Basin, Wyoming typically contain elevated concentrations of selenium.

Impoundment of streams receiving produced water tends to increase waterborne selenium concentrations through evaporative concentration and create a hazard for migratory aquatic birds. Fish also can bioaccumulate selenium directly from the water as well as from their diet. Top level consumers in aquatic systems, such as waterfowl can readily accumulate selenium concentrations leading to low reproduction, embryonic deformities and increased mortality (Ohlendorf et al. 1988).

Selenium bioaccumulates in aquatic vegetation and invertebrates. Fish also can bioaccumulate selenium directly from the water and from their diet. Waterfowl can readily accumulate selenium concentrations leading to low reproduction rates, embryonic deformities and increased mortality (Ohlendorf et al. 1988). Selenium can concentrate in the food chain up to 2,000 times over the concentration in the water (Ohlendorf 1989). For example, at the Kendrick irrigation project, west of Casper, Wyoming, physical deformities and poor reproductive success in American avocets and eared grebes resulted from elevated selenium concentrations. The median concentration of dissolved selenium in water samples from two closed basin ponds located in the Kendrick irrigation project were 38 and 54 μg/L and with bioaccumulation of selenium in food items from these ponds, aquatic birds suffered from impaired reproduction and embryonic deformities (See et al. 1992).

CBM produced water can also contain a variety of other trace elements including arsenic, barium, and zinc. CBM produced water also often contains high concentrations of dissolved salts, making it unsuitable for irrigation and toxic to native plants. Soil irrigated with this water accumulates salts which destroy soil structure and inhibit adequate water uptake by plants. The sodium absorption ratio (SAR) of produced water typically is 10-12 times the level beyond which soil will maintain structure to support plant productivity. While there is debate over absolute values for acceptable limits for SAR, there is consistent agreement that high SAR water is a source of significant impairment for many soils, particularly irrigated soils and soils located in arid or semi-arid regions (Bauder 2002). Consequently, important wildlife habitat may be severely impacted or eliminated by surface discharge of produced water. For example, riparian or stream side areas are the single most productive wildlife habitat type in North America. They support a greater variety of wildlife than any other habitat. Riparian vegetation plays an important role in protecting streams, reducing erosion and sedimentation as well as improving water quality, maintaining the water table, controlling flooding, and providing shade and cover. Impacts to these areas should be avoided whenever possible. Additionally, discharging large volumes of produced water into rivers and streams can severely impact aquatic species and their habitats. Potential impacts include changes in stream temperature and hydrology, and increased erosion and sedimentation resulting in the destruction of fish spawning grounds and compromising fish and aquatic invertebrate growth and survival.

The construction of reservoirs and associated facilities for disposal of water produced during the development of CBM wells can adversely affect groundwater and surface water. Infiltration or percolation of CBM produced water containing high levels of salts or trace elements can reach groundwater and eventually seep out and reach surface waters. Additionally, groundwater could seep into low areas or basins in upland sites and create wetlands which would attract migratory birds and other wildlife.

Reservoirs typically increase the level of shallow aquifers and this increased water table level can extend a considerable distance down gradient within the water table (Winter et al. 1998). If site conditions are suitable, the shallow aquifer can surface downstream of the CBM produced water reservoir creating pools attractive to wildlife. Additionally, infiltration of CBM produced water from the reservoir through the underlying strata can leach naturally-occurring salts and trace elements. CBM produced water with elevated salts and or trace elements would result in greater concentrations of these contaminants in the groundwater than would otherwise be present if they are leached from the strata. Pitt et al. (1994) state that "once contamination with salts begins, the movement of salts into the groundwater can be rapid."

Bartos and Ogle (2002) documented maximums of 4,020 mg/L (parts per million) for total dissolved solids (TDS), 4,330 μS/cm for specific conductance, 1,000 mg/L for sodium, and 39 mg/L for magnesium in groundwater from CBM wells in the PRB in Wyoming. The maximum sodium and specific conductance concentrations found by Bartos and Ogle (2002) were above levels documented as causing poor growth of mallard ducklings (Mitcham and Wobeser 1988). An increase of sodium and conductivity to levels above 2,550 mg/L and 20,000 microSiemens per centimeter (μS/cm), respectively, can cause duckling mortality (Mitcham and Wobeser 1988).

CBM produced water often contains high concentrations of dissolved salts, making it toxic to native plants. Bartos and Ogle (2002) characterized groundwater samples from coalbed aquifers in the PRB in the medium to very high salinity hazard classes which are not suitable for application on soil. Important wildlife habitat may be severely impacted or eliminated by the impoundment of CBM produced water in the high and very high salinity hazard class of groundwater aquifers. Seepage of this water can alter riparian or stream side vegetation which protects streams, reduces erosion and sedimentation as well as improving water quality, maintains the water table, controls flooding, and provides shade and cover for wildlife. Additionally, mineral deposits, such as halite (salt) and gypsum, in exposed reservoir sediments could prevent the establishment of vegetation at the reservoir site after discharge of CBM produced water ceases.

A CBM reservoir placed on or immediately upstream of an intermittent stream reach could result in the potential contamination of the shallow ground water. This contamination could in turn potentially affect riparian vegetation or make elevated trace elements available to aquatic organisms inhabiting those stream reaches and ultimately wildlife feeding on those organisms.

Some ephemeral streams contain deep pools that do not dry up except during extreme drought. Pools in ephemeral draws or streams provide habitat for aquatic life adapted to withstand dry conditions by forming cysts and burrowing into the substrate. These pools also provide habitat for migratory aquatic birds. Downstream subsurface migration and eventual emergence of CBM produced water may substantially impact the water quality of pools in ephemeral draws.

Figures 4, 5, 6, and 7 demonstrate the distribution of conductivity, sodium, SAR, and TDS in CBM produced water in the PRB. The conductivity, sodium, and SAR maps are based on data obtained from Cindy Rice, U.S. Geological Survey, Denver, Colorado (personal communications, February 2004) . The TDS map was obtained from the Water Resources Research Institute (1981) in Laramie, Wyoming. In general, the highest concentrations of sodium and SAR and the highest conductivities occur in the Powder River, Tongue River, and Clear Creek watersheds.

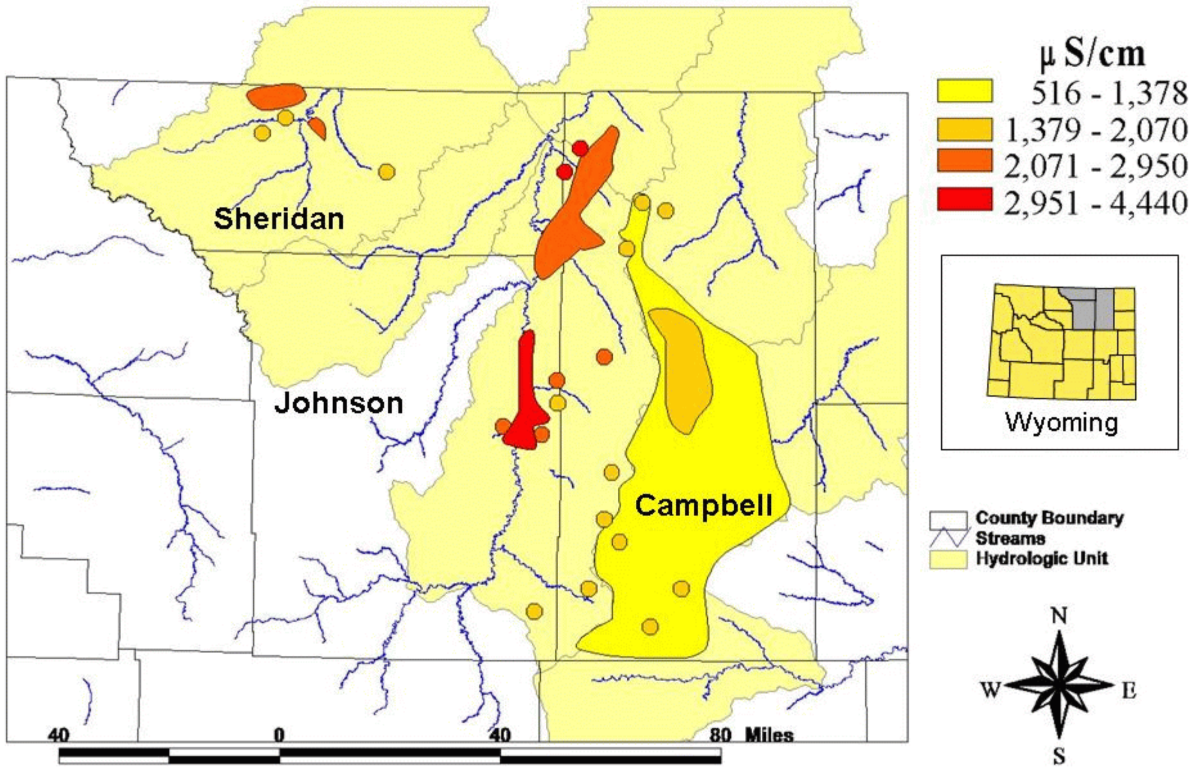


Figure 4. Electrical conductivity (in µS/cm) in water from coalbed methane wells in the Powder River Basin, Wyoming (from Cindy Rice, U.S. Geological Survey, Denver, Colorado, personal communications, February 2004.

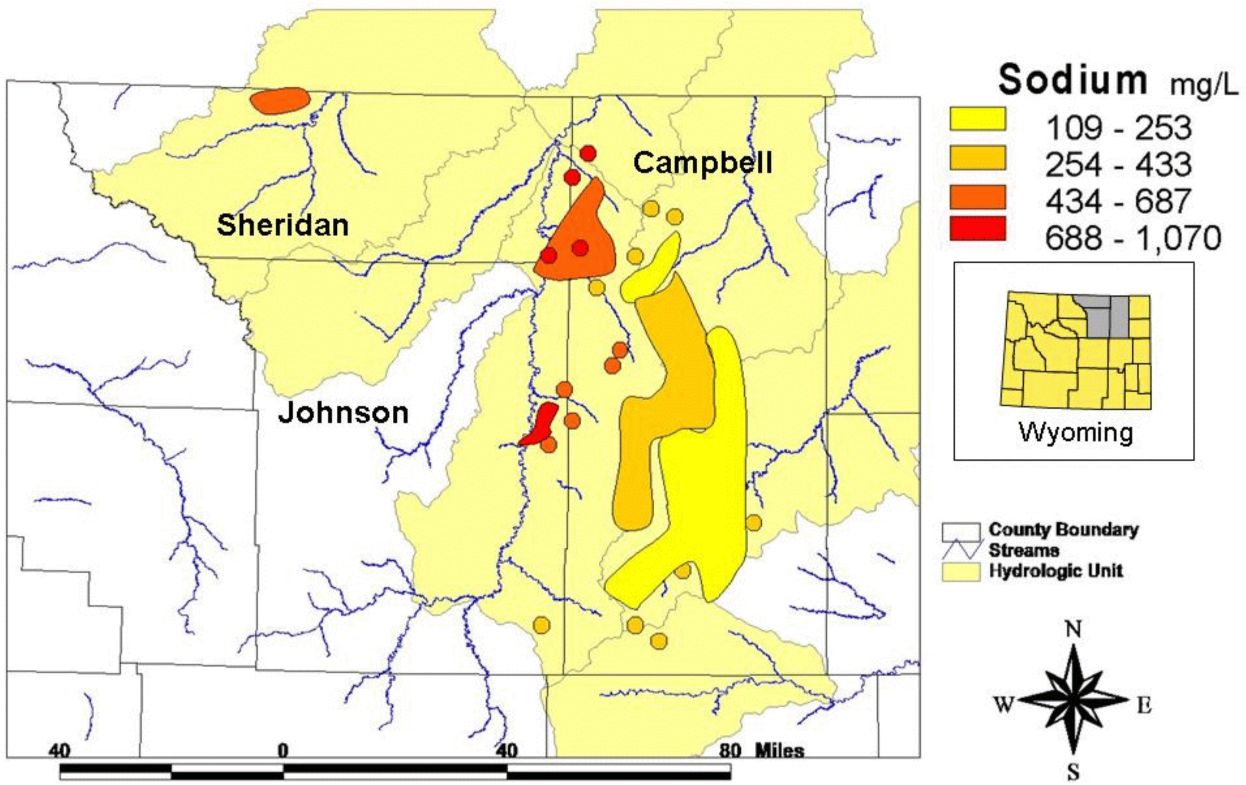


Figure 5. Sodium (in mg/L) in water from coalbed methane wells in the Powder River Basin, Wyoming (from Cindy Rice, U.S. Geological Survey, Denver, Colorado, personal communications, February 2004).

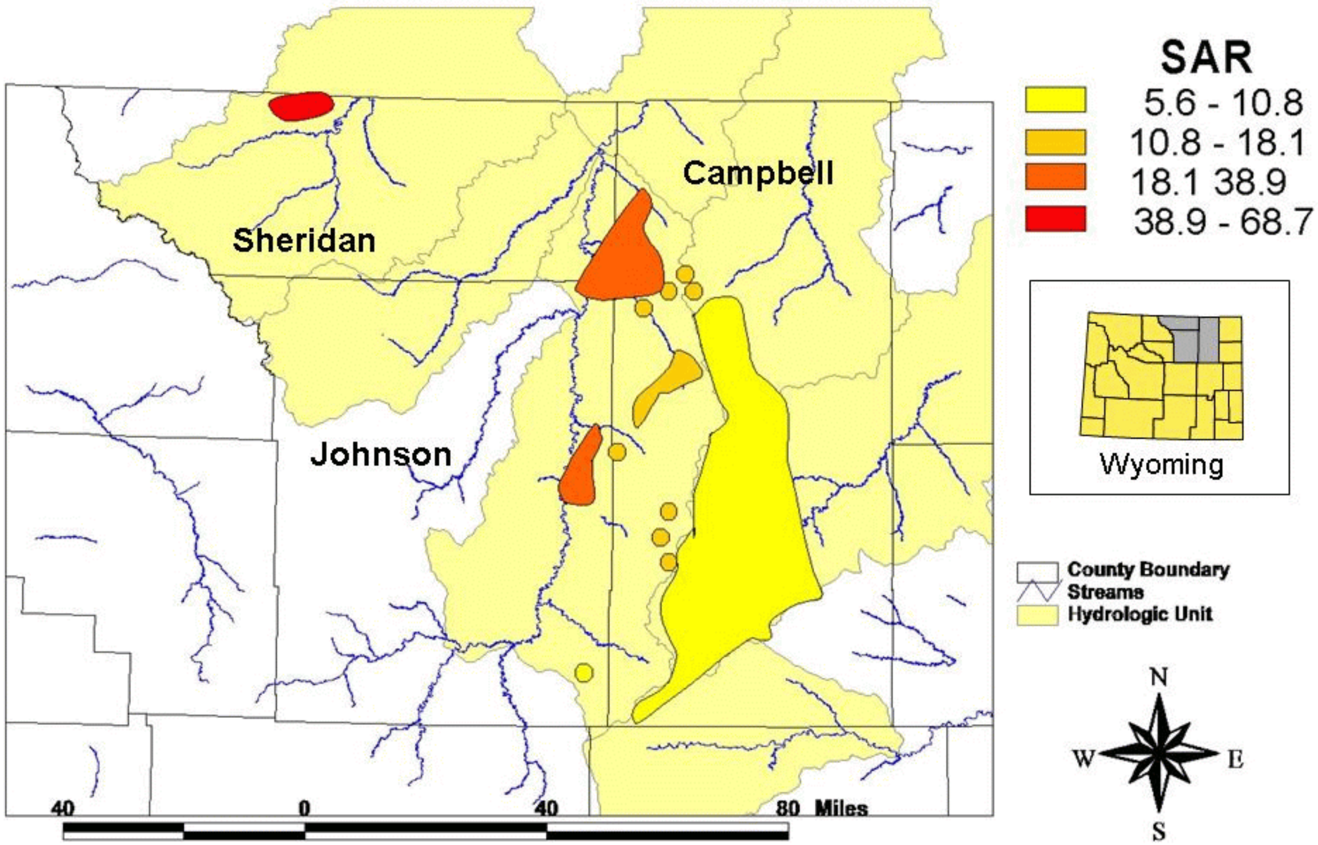
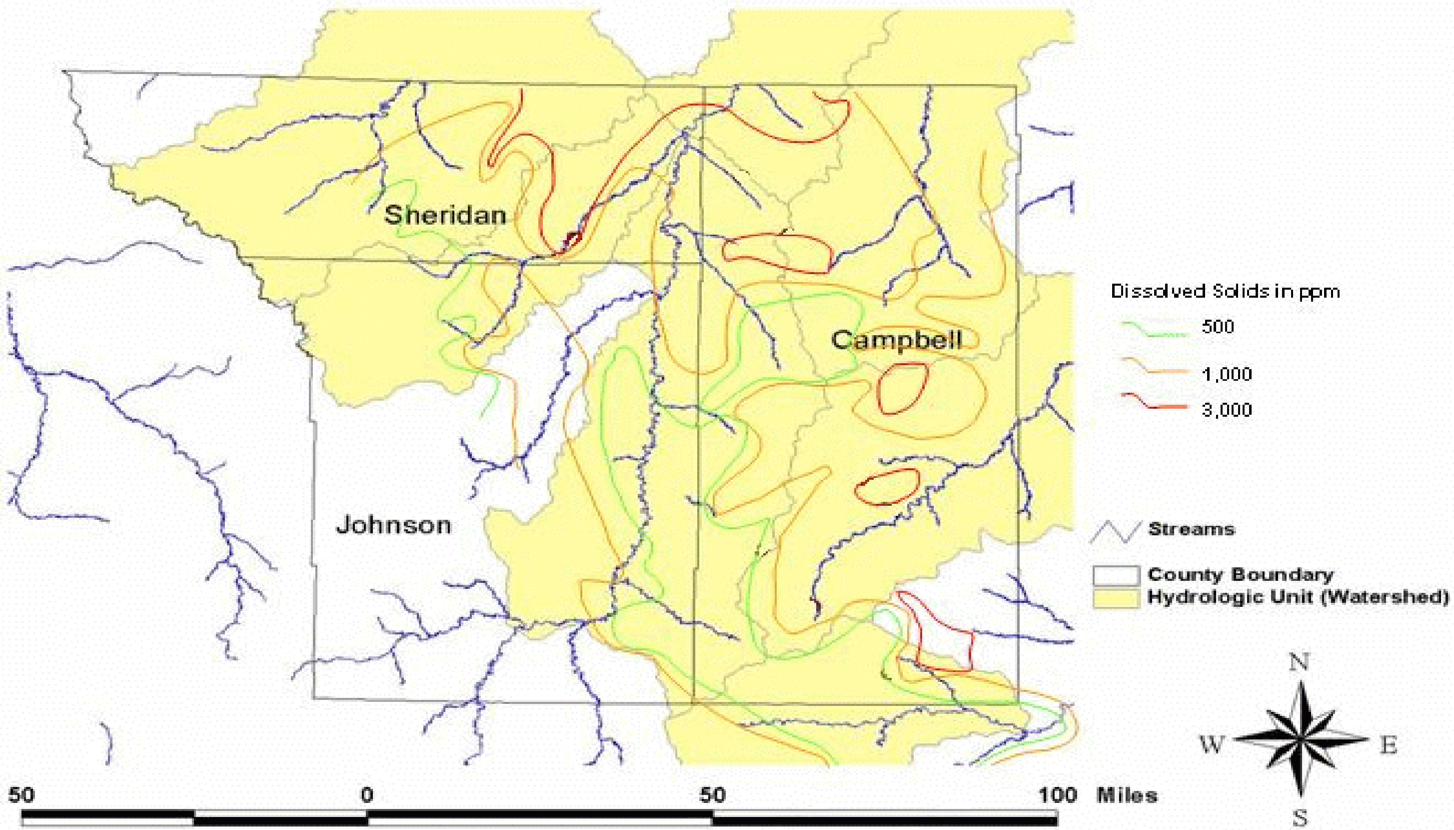


Figure 6. Sodium adsorption ratio (SAR) in water from coalbed methane wells in the Powder River Basin, Wyoming (from Cindy Rice, U.S. Geological Survey, Denver, Colorado, personal communications, February 2004).



Source: [http://deq.state.wy.us/wqd/cbm.asp] *Dissolved Solids Map of Wasatch/Fort Union Aquifer System Water, Powder River Basin, Wyoming* from Volume I-B, *Occurrence and Characteristics of Ground Water in the Powder River Basin, Wyoming,* Water Resources Res. Institute, Univ. Wyoming, 1981.

Figure 7. Total dissolved solids (in mg/L) in water from coalbed methane wells in the Powder River Basin, Wyoming.

STUDY AREA

This study was conducted in the PRB in Campbell, and Sheridan counties, Wyoming (Figure 8) from 2000 to 2002. The PRB is semi-arid with average annual precipitation ranging from 12 to 16 inches and a pan evaporation rate of 60 inches per year. Specific site locations sampled in this study are provided in Table 2.

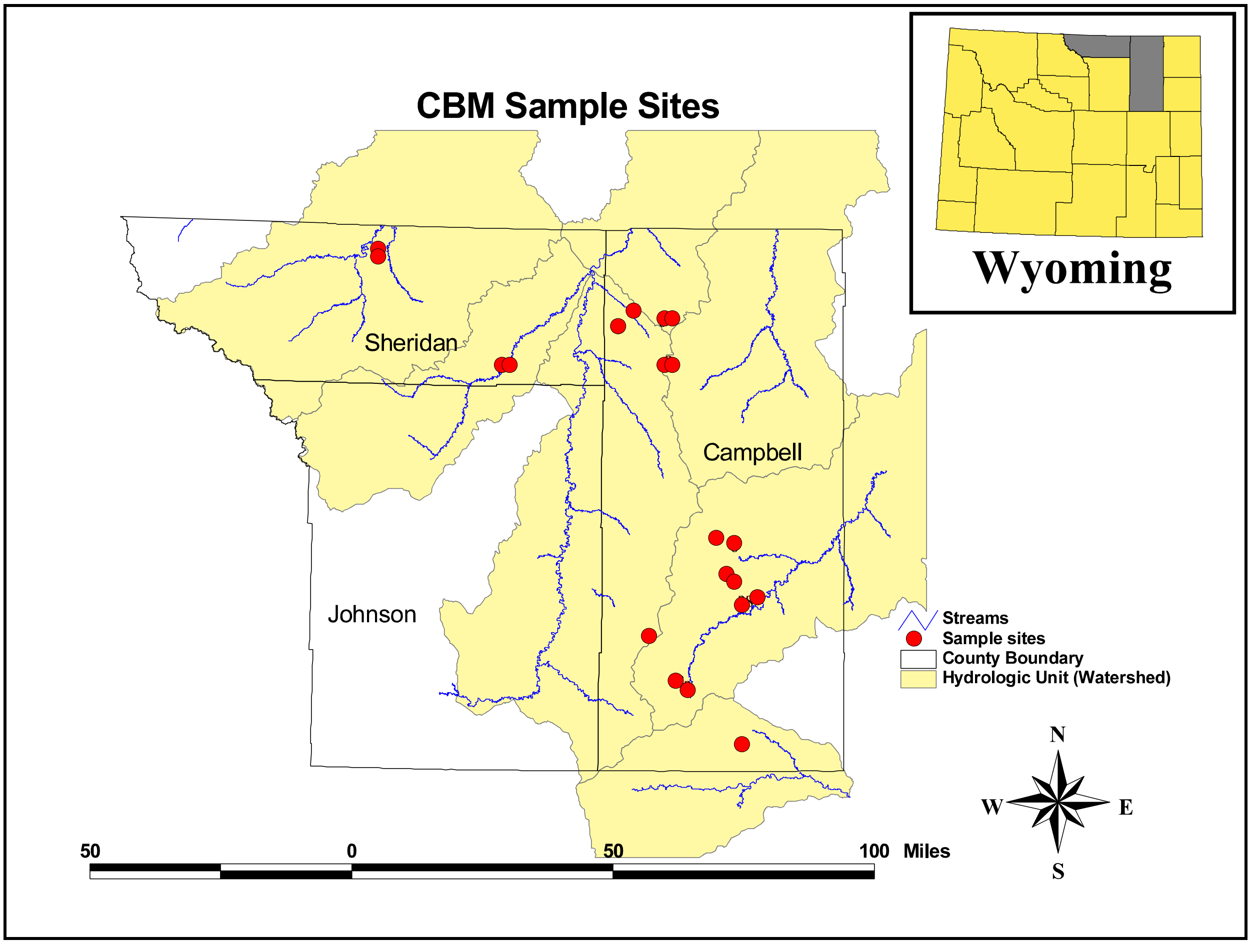


Figure 8. Location of study area and sample sites in the Powder River Basin, Wyoming.

Table 2. Sampling locations for the coalbed methane produced water study in the Powder River Basin, Wyoming.

Site Name	NPDES #	Latitude	Longitude	Township	Range	Section
LPD Pit	WY0046574	44.925900	-106.890602	57 N	83 W	9
Section 16 - # 2	WY0046531	44.920101	-106.883301	57 N	83 W	16
Section 16 - # 1	WY0046531	44.913898	-106.882004	57 N	83 W	16
Groves Ranch	WY0039004	43.870998	-105.825600	45N	75W	13
Rhoades Ranch 1	WY0043770	44.619801	-106.387802	54N	79W	29
Rhoades Ranch 2	WY0043770	44.618301	-106.392799	54N	79W	29
Rhoades Ranch 3	WY0043770	44.621300	-106.378799	54N	79W	28
Appel Ranch	WY0037907	44.142300	-105.568100	48N	73W	13
K Bar/State Land	WY0037435	43.749802	-105.695900	44N	74W	36
North Groves	WY0038750	43.735199	-105.671204	44N	73W	6
SW Carter	WY0039578	44.040501	-105.525200	47N	72W	20
Redtop Pod	WY0035807	44.028900	-105.495102	47N	72W	22
Viper Pod	WY0046949	43.971699	-105.436096	46N	71W	7
Osborne Trust	WY0035807	43.972401	-105.465897	46N	72W	11
Clark Ranch	WY0039063	44.724201	-105.948196	44N	76W	36
Bower/State Land	WY0037052	43.572498	-105.450302	42N	72W	36
Sorenson 4	WY0039641	44.634666	-105.752983	54N	74W	27
Sorenson 2	WY0039861	44.750084	-105.762680	55N	74W	16
Sorenson 3	WY0039624	44.625252	-105.764214	54N	74W	28
Lynde Trust Site	WY0035441	44.123981	-105.494766	48N	72W	22
Sorenson 1	WY0039861	44.745785	-105.779251	55N	74W	16
West	WY0041033	44.774284	-105.891136	55N	75W	4

The PRB is bounded in the west by the Bighorn Mountains and on the east by the Black Hills. Waterways that drain the PRB include the Tongue, Powder, Little Powder, Belle Fourche, and Cheyenne Rivers which flow into the Missouri River system. The PRB consists of rolling, uplands that are typically characterized as short-grass prairie, mixed-grass prairie, and sagebrush (Merrill et al. 1996). Wetlands in the PRB include riverine wetlands, associated with perennial streams, small ponds or playas in topographical depressions, and artificially constructed impoundments ranging from small stock ponds to large reservoirs.

Geologic formations in the PRB include the Oligocene White River, the Eocene Wasatch, and the Paleocene Fort Union formations (US BLM 2003). These formations typically consist of sandstone and shales (Love and Christiansen 1985). Upland soils in the PRB are derived from sandstone, shale and siltstone and stream alluvium (US BLM 2003). The soils are low in organic matter, are alkaline, and range in texture from clay loams to sandy loams (US BLM 2003).

Groundwater aquifers that occur at or near the land surface in the PRB are associated with unconsolidated Quaternary alluvial deposits along rivers, or in lower Tertiary sandstones and coal beds (US BLM 2003). Groundwater aquifers include: Quaternary alluvial; Wasatch; Fort Union; Lebo; and Tullock formations (US BLM 2003). Water quality in these aquifers varies; however, groundwater in the Powder River drainage is usually of poorer quality than occurs in other areas of the PRB. Groundwater in the Powder River alluvial aquifer is dominated by sodium, calcium and sulfate ions (Ringen and Daddow 1990). Sodium sulfate and sodium bicarbonate are the dominant water types in the Wasatch aquifer with TDS ranging from 227 to 8,200 mg/L (US BLM 2003). The Fort Union aquifer is primarily a sodium bicarbonate type with TDS ranging from 200 to 3,000 mg/L. Potable freshwater typically contains less than 1,000 mg/L TDS and waters with TDS concentrations greater than 1,000 mg/L but less than 35,000 mg/L are considered brackish (Drever 1988). Brackish waters with TDS concentrations ranging from 1,000 to 3,000 mg/L are suitable for livestock consumption but can cause temporary and mild diarrhea (Osweiler et al. 1976).

Clearwater et al. (2002) summarized the quality of CBM produced water in the PRB and reported that conductivity increases from <1,000 µS/cm southeast of the Belle Fourche River to 3,000 µS/cm immediately east of the confluence of Clear Creek with the Powder River. CBM produced water near the Tongue River also has high conductivity ranging from 1,630 to 2,180 µS/cm (Clearwater et al. 2002). TDS concentrations also follow the same pattern as conductivity with low concentrations ranging from 400 to 500 mg/L in the southeast to highs ranging from 985 to 2,280 mg/L east of the Powder River (Clearwater et al. 2002).

The SAR of CBM produced water typically is 10-12 times the level beyond which soil will maintain structure to support plant productivity. Soil irrigated with this water accumulates salts that destroys soil structure and inhibits water uptake by plants. While there is debate over absolute values for acceptable limits for SAR, there is consistent agreement that high SAR water is a source of significant impairment of many soils, particularly irrigated soils and soils of arid or semi-arid regions (Bauder 2002). Consequently, important wildlife habitat may be severely impacted or eliminated by surface discharge of produced water characterized by high SAR values.

METHODS

We obtained water quality data from existing CBM produced water discharges permitted under NPDES from WDEQ. Locations with discharges exceeding water quality criteria and in the case of selenium, values above 2 μg/L, were considered possible sampling sites for this study.

During the first phase of the study in 2000 we obtained information on CBM produced water enhanced wetlands from the U.S. Bureau of Land Management and the WDEQ. We visited these sites and selected wetlands for additional contaminants evaluation because they had breeding aquatic birds, or submerged aquatic vegetation, and aquatic invertebrates and were closed basins receiving CBM produced water or were impoundments with minimal flow-through.

In the second phase of the study in 2001, we collected water, sediment, aquatic vegetation, aquatic invertebrates, and fish or amphibians from wetlands receiving CBM produced water. The initial study plan included collecting bird eggs and bird livers. However, since there were few or no nests or waterfowl broods at some of the wetland sites, we did not attempt to collect bird eggs and livers.

Water Samples

During the 2000 season, we collected water from nine CBM produced water discharges and submitted these samples for trace element analyses. The nine discharges included the following sites: Appel, Clark, Bower, Yates, North Groves, SW Carter, Redtop Pod, Viper Pod, and Osborne Tract (Table 1). During the 2001 season, we collected water from five CBM produced water discharges and receiving wetlands (Lynde, Sorenson 3, West, Appel, and Bower sites). Water samples were collected in 1-liter chemically-clean polyethylene jars with teflon-lined lids. The pH of the water samples collected for chemical analyses was lowered to approximately 2.0 with laboratory-grade nitric acid.

In 2002, water samples were collected from seven closed containment impoundments designed for the disposal of CBM produced water with high SARs by infiltration and evaporation. The seven impoundments were located at the following sites: LPD Pit, Section 16 # 2; Section 16 #1; Rhoades Ranch; and Groves Ranch (Table 1). Water samples were also collected from the CBM discharges associated with the closed containment impoundments. These samples will provide baseline data on trace elements, conductivity and TDS if other investigators wish to determine the effects of evaporation on the concentrations of these constituents.

Sediment Samples

Composite sediment samples were collected from eight wetland sites receiving CBM produced water: Lynde, Sorenson 1, Sorenson 2, Sorenson 3, Little Thunder Reservoir, West, Appel, and Bower sites. Sediment was collected with an Ekman dredge and a stainless steel spoon rinsed in de-ionized water and acetone. The sediment was placed in Whirl-pak® bags and frozen.

Aquatic Vegetation Samples

We collected pondweed (*Potamogeton* spp.) samples from all wetland sites except the Sorensen 2 site, because no submerged aquatic vegetation was present, nor from the Appel Ranch wetland where we collected water milfoil (*Myriophyllum* spp.) instead because pondweed was not present. Aquatic vegetation samples were collected by hand, placed in Whirl-pak® bags and immediately frozen.

Aquatic Invertebrate Samples

We collected waterboatmen (Family Corixidae) from the Lynde Trust and Sorensen 3 wetland sites. Backswimmers (Family Notonectidae) were collected from the Appel Ranch and Bowers-State wetland sites. Odonates (Order Odonata) were collected from the Appel Ranch wetland site. Vegetation samples were collected by hand. Invertebrate samples were collected using a dip net or light traps as described by Espinosa and Clark (1972) and placed in 40-ml chemically-clean glass vials and frozen.

Fish and Salamander Samples

We collected fathead minnows (*Pimephales promelas*), black bulhead (*Ictalurus melas*) and tiger salamanders (*Ambystoma tigrinum*) in minnow traps. Black bulhead were collected from the Little Thunder Reservoir and fathead minnows were collected from the Lynde Trust wetland site. Fish were not present at the other wetland sites. Tiger salamanders were collected from the Appel Ranch, Bowers-State, and Sorensen 3 wetland sites. Fish and tiger salamander samples were placed in Whirl-pak® bags and immediately frozen after collection.

Laboratory Analyses

Water samples collected from CBM -produced water discharges in 2000 were submitted to the Trace Element Research Laboratory (TERL) at Texas A&M University, in College Station, Texas for analyses. Water, sediment and biota samples collected during the second phase of the study in 2001 were submitted to the Research Triangle Institute Laboratory (RTIL) at Research Triangle Park, North Carolina for analyses. Water samples collected in 2002 were submitted to RTL. TERL and RTIL are under contract with the Service's Analytical Control Facility (ACF) at Shepherdstown, West Virginia for trace element analyses. Trace element analyses included scans for arsenic, mercury, and selenium using atomic absorption spectroscopy. Inductively Coupled Plasma Emission Spectroscopy was used to scan a variety of elements including barium, boron, copper, lead, vanadium and zinc. Mercury samples were digested under reflux in nitric acid. Other samples were digested under reflux in nitric and perchloric acids. ACF conducted Quality Assurance/Quality Control on all samples analyzed by TERL and RTIL. Quality control samples in the form of procedural blanks, matrix spikes, duplicates, and standard reference materials (ARM) were analyzed with each batch of 20 or fewer samples. All analytical data for sediment and biota are reported in dry weight unless otherwise noted. SYSTAT® statistical software was used to perform paired t-tests on water quality data.

RESULTS

Water in Wetlands and Associated CBM Discharges

In general, trace elements were below WDEQ acute and chronic aquatic life criteria with the exception of iron, manganese, lead, and copper (Table 3). Exceedances of WDEQ's 1,000 µg/L chronic criterion for iron were documented at the CBM produced water discharge at the Appel Ranch site (1,790 µg/L) and at closed basin wetland at the Bower/State Land site (10,400 µg/L). Iron concentrations in all CBM produced water discharges and receiving wetlands sampled exceeded the lowest chronic values (LCVs) reported by Suter and Tsao (1996) for fish, daphnids, and aquatic plants.

Waterborne manganese in a closed basin wetlands at the West and Bower/State Land sites were 2,090 and 234 µg/L, respectively, and exceeded the WDEQ chronic criteria, calculated based on hardness. Lead concentrations in water collected from wetlands at the Bower/State Land and West sites were 14.4 and 28.3 µg/L, respectively and exceeded the WDEQ chronic criterion which is dependent on hardness. Hardness as $CaCO_3$ for water collected from wetlands at the Bower/State Land and West sites was 52 and 4,685 mg/L, respectively. The chronic values calculated for lead based on the hardness for these two sites were 1.2 and 11 µg/L.

Copper concentrations in water exceeded the WDEQ acute criterion, calculated based on hardness, for CBM produced water discharges at the Bower/State Land; Lynde Trust; and Sorenson 3 sites. The chronic criterion for copper was exceeded in water collected from wetlands at the Bower/State Land; Lynde Trust; Sorenson 3; and Appel Ranch sites.

Cadmium concentrations in water collected from the CBM produced water discharges and receiving wetlands at the Sorensen 3 and West Ranch sites ranged from 6.7 to 9.3 µg/L and exceeded the 3 µg/L threshold identified by Eisler (2000) as potentially hazardous to freshwater aquatic life.

Results of trace element concentrations in CBM produced water discharge samples are presented in Appendix A and Appendix B.

Water in Closed Containment Impoundments and Associated Discharges

Water quality results from CBM produced water collected from closed containment impoundments and their associated discharges are presented in Appendix C. Although several trace elements such as aluminum, boron, chromium, iron, and manganese were generally higher in the closed containment impoundments than in the respective discharges, the differences were not statistically significant (paired t-test, $p<0.05$). Waterborne selenium concentrations in six of the seven closed containment impoundments and all seven associated discharges exceeded the 2 µg/L threshold for selenium bioaccumulation in sensitive species of fish and aquatic birds (Appendix C).

Sediment

Mean trace element concentrations in bottom sediment collected from wetlands receiving CBM produced water generally were below background values as reported by Shacklette and Boerngen (1984). Trace elements that exceeded background include arsenic, boron, beryllium, copper, manganese, nickel, lead and zinc (Table 4)(Appendix D). Arsenic, cadmium, nickel and zinc in bottom sediment from three wetland sites were above MacDonald et al's (2000) consensus-based threshold effects concentrations (TECs)(Table 5). TECs are defined by MacDonald et al. (2000) as the concentration of a chemical in sediment "below which adverse effects on sediment-dwelling organisms are not expected to occur." Arsenic, cadmium, nickel and zinc did not, however, exceed the consensus-based probable effect concentration (PEC) which MacDonald et al. (2000) define as the concentration of a chemical in sediment "above which adverse effects on sediment-dwelling organisms are likely to be observed."

Table 3. Concentrations of copper, iron, lead, and manganese (in µg/L) in water from coalbed methane produced water discharges and receiving wetlands in Sheridan and Campbell counties, Wyoming (2000 - 2001).

CBM Produced Water Discharges						
Sample ID	Site Name	Hardness*	Cu	Fe	Mn	Pb
CBM001	Appel	228	0.3	1,790	35	0.08
CBM003	Bower	79	0.6	688	9	0.13
CBMDLT1	Lynde	44	8.5	176	3.1	BDL
CBMDSOR3	Sorenson 3	71	15.5	686	48.5	BDL
CBMDWES1	West	304	16.7	851	32	BDL
Wetlands Receiving CBM Produced Water						
Sample ID	Site Name	Hardness	Cu	Fe	Mn	Pb
CBMWAPR1	Appel	130	16.5	116	30.3	BDL
CBMWBOW1	Bower	52	26.9	10,400	234	14.4
CBMWLT1	Lynde	110	14.4	627	35.3	BDL
CBMWSR3A	Sorenson 3	47	15.3	941	31.4	BDL
CBMWWES1	West	4,685	19.1	479	2,090	28.3

* Hardness as $CaCO_3$ in mg/L

Aquatic Vegetation

Boron in aquatic vegetation (Table 6, Appendix E) from all sites except Sorensen 3 exceeded the 30 µg/g (parts per million) level documented to effect growth in ducklings (Smith and Anders 1989). Mean cadmium concentrations in pondweed from the Bowers-State wetland site and Little Thunder Reservoir were 0.145 µg/g and 0.123 µg/g, respectively, slightly above the 0.1 µg/g wet weight level that Eisler (2000) recommends should be "viewed with caution" in terms of wildlife dietary levels; but below the 2 µg/g dietary threshold for birds reported by Furness (1996). Mean chromium concentrations in pondweed from the Bowers-State and West Ranch wetland sites were 26.12 µg/g and 13.76 µg/g, respectively, and exceeded the wildlife dietary threshold of 10 µg/g recommended by Eisler (2000).

Aquatic Invertebrates

Trace elements in aquatic invertebrates collected from all wetland sites generally were below concentrations known to cause adverse effects to fish and birds (Appendix F). Boron concentrations were elevated in aquatic invertebrates collected from the Appel Ranch, Lynde Trust and Sorensen 3 wetland sites. The invertebrate composite samples from the Appel Ranch, and Lynde Trust wetland sites had boron concentrations of 30.4 µg/g, and 98.6 µg/g, respectively, which exceeded the 30 µg/g level documented to reduce growth in ducklings (Smith and Anders 1989). The mean boron concentration in aquatic invertebrates collected from the Sorensen 3 wetland site was 42.2 µg/g.

Mean cadmium concentrations in aquatic invertebrates from the Bowers-State, and Sorensen 3 wetland sites were 0.68, and 1.4 µg/g, respectively. The wet weight concentrations for these sites were 0.43, and 0.197 µg/g for the Bowers-State and Lynde Trust sites, respectively, above the 0.1 µg/g wet weight level that Eisler (2000) recommends should be "viewed with caution" in terms of wildlife dietary levels. One waterboatmen sample collected from the Lynde Trust wetland site had a cadmium concentration of 0.13 µg/g dry weight (0.18 µg/g wet weight).

Fish

Trace elements in fish collected from Little Thunder Reservoir and the Lynde Trust wetland site generally were below concentrations known to cause adverse effects to fish with the exception of chromium in fathead minnows from the Lynde Trust wetland site (Appendix G). Chromium concentrations in fathead minnows from the Lynde Trust wetland site ranged from 24.4 µg/g to 307 µg/g with a mean concentration of 150.7 µg/g, exceeding the 4 µg/g level that Eisler (2000) states "should be viewed as presumptive evidence of chromium contamination."

Tiger Salamanders

Trace element tissue residue thresholds for amphibians are unknown. Mean chromium concentrations in tiger salamanders from Appel Ranch, Bowers-State, and Sorensen 3 wetland sites ranged from 18.6 µg/g to 137 µg/g, and were well above Eisler's (2000) 4 µg/g concern level (Appendix G).

Table 4. Trace element concentrations (mean and range) in µg/g, and the proportions that exceeded background concentrations (as reported by Shacklette and Boerngen 1984) in sediment from wetlands receiving coalbed methane produced water discharges in Campbell County, Wyoming (2001).

Element	Background (in µg/g)	Site					
		Appel Ranch	Bowers-State	Lynde Trust	Sorensen 2	Sorensen 3	West Ranch
Arsenic	5.5	7.5 (4.6 - 13.1) [4 of 5]	4.7 (3.1 - 7.6) [1 of 5]	3.8 (2.3 - 5.0) [0 of 5]	6.4 (4.9 - 11.5) [1 of 5]	4.9 (2.6 - 6.6) [2 of 5]	8.5 (4.3 - 15.6) [3 of 5]
Boron	23	13.0 (11.3 - 15.6) [0 of 5]	10.8 (6.8 - 13.4) [0 of 5]	11.8 (6.8 - 14.7) [0 of 5]	17.5 (13.6 - 30.1) [0 of 5]	11.1 (6.4 - 16.7) [0 of 5]	26.6 (13.1 - 37.4) [3 of 5]
Beryllium	0.68	0.74 (0.56 - 0.84) [4 of 5]	0.98 (0.857 - 1.1) [5 of 5]	0.62 (0.35 - 0.77) [3 of 5]	0.70 (0.53 - 1.0) [2 of 5]	0.60 (0.44 - 0.79) [1 of 5]	1.12 (0.78 - 1.59) [5 of 5]
Copper	19	17.7 (13.4 - 20.7) [1 of 5]	19.0 (15.8 - 22.9) [2 of 5]	14.2 (6.6 - 19.6) [1 of 5]	17.4 (14.6 - 20.7) [2 of 5]	13.1 (5.5 - 23.8) [1 of 5]	20.6 (16.2 - 24) [4 of 5]
Manganese	380	245 (208 - 326) [0 of 5]	356 (173 - 699) [2 of 5]	228 (131 - 280) [0 of 5]	403 (313 - 693) [1 of 5]	265 (104 - 428) [1 of 5]	1,407 (436 - 2,924) [5 of 5]
Nickel	15	18.4 (14 - 21.6) [4 of 5]	18.2 (14.5 - 21.7) [4 of 5]	15.0 (8.2 - 19.2) [3 of 5]	14.0 (12.4 - 15.7) [1 of 5]	15.0 (9.0 - 24.4) [2 of 5]	29.0 (16.9 - 42) [5 of 5]
Lead	16	13.4 (12.5 - 14.9) [0 of 5]	18.6 (16.9 - 19.8) [5 of 5]	11.8 (6.5 - 15.6) [0 of 5]	11.0 (8.1 - 13.3) [0 of 5]	11.1 (6.4 - 18.4) [1 of 5]	14.0 (12.3 - 16.6) [1 of 5]
Zinc	55	66.3 (57.2 - 78.5) [5 of 5]	67.2 (55.8 - 75.9) [5 of 5]	52.3 (29.6 - 66.8) [3 of 5]	46.8 (41.2 - 55.6) [1 of 5]	45.9 (33.4 - 58.3) [1 of 5]	139.7 (81.9 - 195) [5 of 5]

Mean
(Minimum - Maximum)
[number of samples above background]

Table 5. Trace elements exceeding consensus-based threshold effects concentrations (in µg/g)(as reported by MacDonald et al. 2000) in sediment from wetlands receiving coalbed methane produced water discharges in Campbell County, Wyoming (2001).

Sample #	**Site**	**Arsenic** **TEC = 9.79**	**Cadmium** **TEC=0.99**	**Nickel** **TEC=22.7**	**Zinc** **TEC = 121**

CBMAPR3	Appel Ranch	13.1			
CBMSSR2D	Sorensen 2	11.5	1.59		
CBMSSR3E	Sorensen 3			24.4	
CBMSWES2	West Ranch	15.6	2.19	38.5	
CBMSWES3	West Ranch	11.7	2.26	42.0	153
CBMSWES4	West Ranch		1.32	26.9	
CBMSWES5	West Ranch		1.28		

Table 6. Boron concentrations (in µg/g) in submerged aquatic vegetation collected from wetlands receiving coalbed methane produced water discharges in Campbell County, Wyoming (2001).

Site	Mean	Minimum	Maximum
Appel Ranch (Water Milfoil)	37.76	33.1	49.2
Bowers-State (Pondweed)	300	221	362
Lynde Trust (Pondweed)	109	41.3	207
Sorensen 3 (Pondweed)	19.6	18.2	21.5
West Ranch (Pondweed)	172	155	208
Little Thunder Reservoir (Pondweed)	324	251	396

Number of samples from each site (n) = 5

DISCUSSION

The Bowers/State and West Ranch wetland sites are terminal sinks that receive CBM produced water. The Sorensen 3 site is a closed containment pond constructed to dispose of CBM produced water through infiltration and evaporation. Three of the wetland sites (Appel Ranch, Lynde Trust, and Sorensen 2) are small impoundments designed to control the flow of CBM produced water into ephemeral streams. The Little Thunder Reservoir is in the Thunder Basin National Grasslands and existed prior to CBM produced water discharge. Exceedance of trace element background concentrations in sediment did not appear related to the site type (flow-through versus terminal sink) as several trace elements were above background in both site types. Arsenic, cadmium, nickel, and zinc in sediments from the West Ranch site (a terminal sink) exceeded the TECs as defined by MacDonald et al. (2000) as the concentration of a chemical in sediment "below which adverse effects on sediment-dwelling organisms are not expected to occur."

Aquatic vegetation was collected from all sites except the Sorensen 2 site where it was not present. Boron concentrations in aquatic vegetation collected from sites where it was present exceeded the 30 μg/g level documented to effect growth in ducklings (Smith and Anders 1989). Cadmium concentrations in aquatic vegetation from the Bowers/State wetland site and the Little Thunder Reservoir were slightly above the 0.1 μg/g wet weight level that Eisler (2000) recommends should be "viewed with caution" in terms of wildlife dietary levels. Chromium concentrations in pondweed from the Bowers/State and the West Ranch sites exceeded the wildlife dietary threshold of 10 μg/g recommended by Eisler (2000).

Cadmium concentrations in aquatic invertebrates from the Bowers/State, Lynde Trust, and Sorensen 3 sites exceeded the 0.1 μg/g wet weight level that Eisler (2000) recommends should be "viewed with caution" in terms of wildlife dietary levels. Chromium concentrations in tiger salamanders from the Appel Ranch, Bowers/State, and Sorensen 3 sites ranged from 18.6 to 137 μg/g and exceeded the 4 μg/g level that Eisler (2000) states "should be viewed as presumptive evidence of chromium contamination." Chromium concentrations in fathead minnows from the Lynde Trust site exceeded the 4 μg/g threshold and ranged from 24.4 to 307 μg/g.

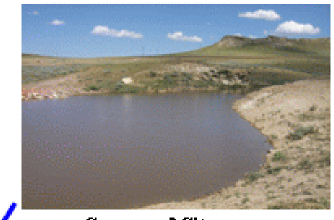
Selenium concentrations in water, sediment, and biota were below threshold levels known to cause adverse effects to sensitive species of fish and aquatic birds, with the exception of CBM produced water discharges and CBM closed containment impoundments. Waterborne selenium concentrations in six of the seven closed containment impoundments and all seven associated discharges ranged from 2.2 to 8.4 μg/L, exceeding the 2 μg/L threshold for bioaccumulation in sensitive species of fish and aquatic birds. Closed containment ponds containing high selenium water may present a risk to aquatic birds using these ponds if the ponds provide a dietary route of exposure through submerged aquatic vegetation or aquatic invertebrates.

Since sediment or soil quality data from the wetland sites prior to the discharge of CBM produced water is not available it is not possible to determine if trace element exceedances are naturally occurring. Exceedances of thresholds for the protection of fish and wildlife in dietary items consumed by aquatic migratory birds indicate that site specific monitoring of water, sediment and biota in wetlands receiving CBM produced water, especially terminal sinks, should be undertaken to conclusively determine ecological risk and prospective injury to biota. Trace elements in terminal sinks are expected to increase over time due to evaporative concentration. Additionally, research conducted by McBeth et al. (2003a) shows that increases in pH in CBM produced water impoundments can increase the solubility and mobility of aluminum, iron, arsenic, selenium, and fluoride. McBeth et al. (2003b) also showed significant increases in specific conductance, TDS, alkalinity, sodium, potassium and SAR “moving north from the Cheyenne River basin to the Little Powder River basin.

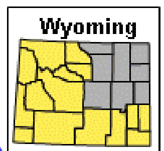
A summary of trace elements exceeding the benchmarks for water, sediment and biota in wetlands receiving CBM produced water are shown below.

LEGEND
Criterion, background, and fish and wildlife threshold values shown in brackets.
Sample size = (n)
Water:
Red values denote exceedance of acute criterion.
Element in ppm [acute criterion]
Blue values denote exceedance of chronic criterion.
Element in ppm [chronic criterion]
Sediment:
Red values denote exceedance of TECs as defined by MacDonald et al. (2000).
Element in ppm [TEC]
All other values exceed background values.
Element in ppm [background]

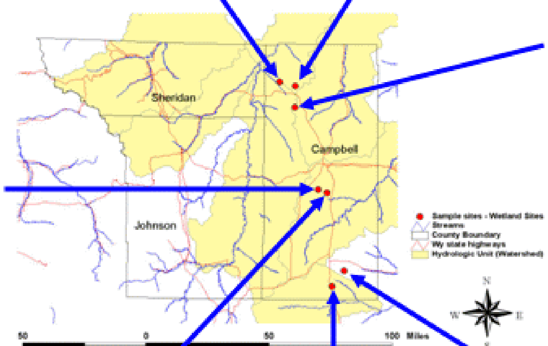
West Ranch Site
Wetland water (n = 1)
· Pb 28.3 ppb [10.94]
Sediment (n = 5)
· As 8.5 ppm [5.5]
· B 26.6 ppm [23]
· Be 1.12 ppm [0.68]
· Cd 1.76 ppm [0.99]
· Mn 1,407 ppm [380]
· Ni 29 ppm [22.7]
· Zn 139.7 ppm [121]
Pondweed (n = 5)
· B 172 ppm [30]
· Cr 13.7 ppm [10]



Sorensen 2 Site
Sediment (n = 5)
· As 6.4 ppm [5.5]
· Be 0.7 ppm [0.68]
· Mn 403 ppm [380]

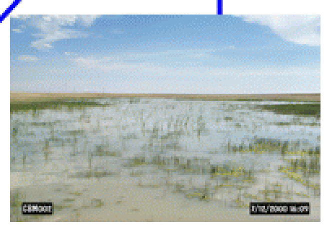


Sorensen 3 Site
CBM produced water (n = 1)
· Cu 15.5 ppb [6.68]
Wetland water (n = 1)
· Cu 15.3 ppb [4.7]
Aquatic Invertebrates (n = 3)
· Cd 1.9 ppm wet weight [0.1]
Tiger Salamanders (n = 5)
· Cr 60 ppm [4]

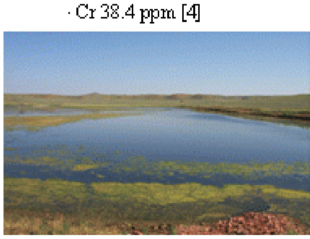


Appel Ranch Site
Wetland water (n = 1)
· Cu 16.5 ppb [11.21]
Sediment (n = 5)
· As 7.5 ppm [5.5]
· Be 0.74 ppm [0.68]
· Ni 18.4 ppm [15]
· Zn 66.3 ppm [55]
Water Milfoil (n = 5)
· B 37.7 ppm [30]
Tiger Salamanders (n = 5)
· Cr 38.4 ppm [4]

Little Thunder Reservoir Site
Pondweed (n = 5)
· B 324 ppm [30]
· Cd 0.12 ppm wet weight [0.1]



Bowers/State Site
Wetland water (n = 1)
· Cu 26.9 ppb [5.12]
Sediment (n = 5)
· Be 0.98 ppm [0.68]
· Ni 18.2 ppm [15]
· Pb 18.6 ppm [16]
· Zn 67.2 ppm [55]
Pondweed (n = 5)
· B 300 ppm [30]
· Cd 0.14 ppm wet weight [0.1]
· Cr 26.1 ppm [10]
Aquatic Invertebrates (n = 5)
· Cd 0.43 ppm wet weight [0.1]
Tiger Salamanders (n = 5)
· Cr 46 ppm [4]



Lynde Trust Site
CBM produced water (n = 1)
· Cu 8.5 ppb [4.44]
Wetland water (n = 1)
· Cu 14.4 ppb [9.72]
Pondweed (n = 5)
· B 109 ppm [30]
Aquatic Invertebrates (n = 1)
· Cd 0.18 ppm wet weight [0.1]
Fathead minnows (n = 5)
· Cr 150.7 ppm [4]

Mean concentrations are shown for sediment and biota except for aquatic invertebrates from the Lynde Trust site where only one composite sample was collected. Benchmarks include water quality criteria, sediment background concentrations as reported by Shacklette and Boerngen (1974), and consensus-based threshold effects concentrations as reported by MacDonald et al. (2000). Fish and wildlife thresholds include dietary and tissue concentrations recommended by Eisler (2002) and Furness (1996). Trace element concentrations in sediment and biota are reported in dry weight unless otherwise noted.

MANAGEMENT RECOMMENDATIONS

Currently, CBM produced water that meets Wyoming water quality standards is discharged into small impoundments creating habitat for aquatic migratory birds and other water-dependent wildlife. However, because ecological threats from contaminated water and sediment can vary from site to site in the PRB, private landowners, public land management agencies and wildlife management agencies should base decisions on whether or not to use CBM produced water for wetland creation and enhancement on site-specific water and sediment quality data.

CBM operators, land managers and landowners should consider the following recommendations to minimize or prevent adverse impacts to fish and wildlife and their habitats from CBM produced water discharges.

- Avoid discharging CBM produced water with selenium >2 µg/L into closed containment pits or ponds for disposal by evaporation.

- Avoid irrigating seleniferous soils with CBM produced water to prevent the leaching of selenium from these soils and mobilization of selenium to downstream wetlands used by fish and aquatic-dependent wildlife.

- Avoid discharge of high SAR CBM produced water to prevent impacts to soils and riparian vegetation.

- Avoid disposal of high TDS/SAR CBM produced water into unlined evaporation ponds to prevent groundwater contamination.

- Avoid disposal of high TDS/SAR CBM produced water into evaporation ponds to prevent potential salt toxicity to aquatic migratory birds using those ponds.

- When disposal of CBM produced water into evaporation ponds cannot be avoided, predictive modeling should be used to determine if sodium, selenium, and or metal concentrations in the water will increase over time and pose a risk to wildlife.

- Consider the soil types and the underlying geology prior to siting CBM produced water impoundments to adequately assess the risk of groundwater contamination.

CBM produced water with elevated selenium: Regulators and CBM operators should not allow the discharge of CBM produced water with selenium concentrations >2 µg/L into closed containment pits or ponds to minimize or prevent eventual increases in selenium concentrations through evaporative concentration. Closed containment ponds characterized by high selenium water may present a risk to aquatic birds using these ponds where a food source in the form of submerged aquatic vegetation or aquatic invertebrates is present.

Irrigation of seleniferous soils: Land owners/managers should avoid irrigating seleniferous soils with CBM produced water to prevent leaching of selenium and its mobilization to downstream wetlands used by fish and aquatic-dependent wildlife.

CBM produced water with elevated SAR: CBM operators should dispose of CBM produced water with elevated SAR in a manner that prevents contamination of groundwater, and downstream riparian and upland soils. Disposal of CBM produced water into closed containment reservoirs can result in groundwater contamination by high levels of salts or trace elements that can eventually seep out and reach surface waters. Additionally, groundwater can seep into low areas or basins in upland sites creating wetlands that attract migratory birds and other wildlife.

An increase of sodium and conductivity to levels above 2,550 mg/L and 20,000 μS/cm, respectively, can cause duckling mortality, especially if an abrupt change from freshwater to saline water occurs (Mitcham and Wobeser 1988). Salt toxicosis occurs when high levels of the sodium ion are ingested without drinking enough freshwater to flush the salt accumulation from the body (Osweiler et al. 1976). Windingstad, et al. (1987) documented salt toxicosis in adult waterfowl in a North Dakota lake with sodium concentrations over 17,000 mg/L. Salt toxicity in wild aquatic birds occurs when they are forced to use saline water during drought conditions or during the winter when freshwater is frozen. The scarcity of freshwater in semi-arid environments aggravates the risk of salt toxicity to aquatic birds using impoundments characterized by saline and especially hypersaline conditions as the affected birds cannot easily move to fresher water to mitigate their ingestion of hypersaline water.

Aquatic birds using hypersaline ponds are susceptible to mortality from salt encrustation. Sodium in the hypersaline water can crystalize on the feathers of birds landing in these waterbodies. The sodium crystals destroy the feathers' thermoregulatory and buoyancy functions causing the bird to drown or die of hypothermia. Salt encrustation on birds has been documented in industrial wastewater ponds with TDS > 200,000 mg/L (Meteyer et al. 1997). Soil irrigated with CBM produced water with elevated SAR accumulates salts that destroys soil structure and inhibits water uptake by plants. High SAR water is a source of significant impairment of many soils, particularly irrigated soils and soils of arid or semi-arid regions (Bauder 2002). Consequently, important wildlife habitats can be severely impacted or eliminated by surface discharges of high SAR produced water.

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APPENDICES

APPENDIX A

Trace elements (in µg/L) in water collected in 2000 from coal bed methane (CBM) produced water discharges in the Powder River Basin, Wyoming.

Sample #	Site	Ag	Al	As	B	Ba	Be	Ca	Cd	Co	Cr	Cu	Fe	Hg
CBM001	Appel	BDL	BDL	0.39	105	1,140	BDL	54,100	BDL	2.67	BDL	0.30	1,790	BDL
CBM002	Clark	0.16	281	2.07	152	970	BDL	28,300	BDL	6.36	0.70	1.60	707	BDL
CBM003	Bower	BDL	60	1.37	116	353	BDL	17,300	0.37	9.84	BDL	0.60	688	BDL
CBM004	Yates	0.08	BDL	0.26	90	582	BDL	40,200	0.53	0.13	BDL	0.40	561	BDL
CBM005	North Groves	BDL	BDL	0.19	70	1,130	BDL	73,200	0.55	0.14	BDL	0.80	1,110	BDL
CBM006	SW Carter	BDL	BDL	0.13	70	659	BDL	32,200	0.38	0.06	BDL	2.20	225	BDL
CBM007	Redtop Pod	BDL	BDL	0.53	80	622	BDL	27,100	0.48	0.06	BDL	0.70	336	BDL
CBM008	Viper Pod	BDL	BDL	0.09	80	541	BDL	28,000	0.35	0.06	BDL	0.80	444	BDL
CBM009	Osborne Tract	BDL	217	0.16	70	507	BDL	26,600	0.69	0.19	BDL	1.60	3,390	BDL

Sample #	Site	K	Mg	Mn	Mo	Na	Ni	Pb	Se	Sr	Tl	V	Zn	Ti
CBM001	Appel	14,700	28,100	35	BDL	246,000	0.50	0.08	0.12	1,150	BDL	BDL	4.30	BDL
CBM002	Clark	17,900	37,000	24	BDL	603,000	2.00	2.01	0.16	1,140	BDL	BDL	2.60	BDL
CBM003	Bower	5,900	8,160	9	BDL	125,000	2.20	0.13	0.09	335	BDL	BDL	2.80	BDL
CBM004	Yates	6,630	10,100	46	BDL	220,000	0.70	0.13	0.29	1,040	BDL	BDL	0.90	BDL
CBM005	North Groves	7,080	14,100	71	BDL	297,000	BDL	BDL	0.47	1,720	BDL	BDL	0.40	BDL
CBM006	SW Carter	11,000	14,300	4	BDL	171,000	BDL	0.07	0.34	611	BDL	BDL	0.40	BDL
CBM007	Redtop Pod	9,650	11,100	5	BDL	153,000	BDL	0.09	0.32	540	BDL	BDL	0.90	BDL
CBM008	Viper Pod	8,820	11,600	4	BDL	177,000	BDL	0.08	0.09	542	BDL	BDL	0.60	BDL
CBM009	Osborne Tract	8,680	11,400	35	BDL	175,000	BDL	0.83	0.10	586	BDL	BDL	1.30	BDL

Sample #	Site	Si	Li
CBM001	Appel	4,700	68
CBM002	Clark	3,800	127
CBM003	Bower	5,400	31
CBM004	Yates	4,200	29
CBM005	North Groves	4,100	36
CBM006	SW Carter	4,400	48
CBM007	Redtop Pod	4,500	42
CBM008	Viper Pod	3,800	51
CBM009	Osborne Tract	4,200	49

APPENDIX B

Trace elements (in µg/L) in water collected in 2001 from coal bed methane (CBM) produced water discharges and receiving impoundments in the Powder River Basin, Wyoming.

Sample #		Al	As	B	Ba	Be	Cd	Cr	Cu	Fe	Hg	Mg	Mn
Lynde													
CBMDLT1	Discharge	<.0222	0.0089	0.104	0.21	<.0004	<.0006	<.00560	0.0085	0.176	<.0002	5.44	0.0031
CBMWLT1	Wetland	0.707	0.018	0.142	0.0509	<.0004	<.0006	0.0087	0.0144	0.627	<.0002	14.7	0.0353
Sorenson 3													
CBMDSOR3	Discharge	<.0222	<.00560	0.086	0.688	<.0004	<.0006	0.0067	0.0155	0.686	<.0002	9.47	0.0485
CBMWSR3A	Wetland	1.16	<.00560	0.098	0.327	<.0004	<.0006	0.0079	0.0153	0.941	<.0002	9.15	0.0314
West													
CBMDWES1	Discharge	0.398	<.00560	0.171	0.424	<.0004	<.0006	0.0093	0.0167	0.851	<.0002	11.4	0.032
CBMWWES1	Wetland	0.14	0.0223	0.681	0.0283	<.0004	<.0006	0.0087	0.0191	0.479	<.0002	1744	2.09
Appel													
CBM001	Discharge	<.0500	0.39	105.00	1,140	<.500	<.0500	<.500	0.30	1.79	<.005	28,100	35
CBMWAPR1	Wetland	0.112	0.019	0.138	0.0723	<.0004	<.0006	0.0084	0.0165	0.116	<.0002	24	0.0303
Bower													
CBM003	Discharge	60	1.37	116	353	<.500	0.37	<.500	0.6	0.688	<.005	8160	9
CBMWBOW1	Wetland	12	0.0085	0.228	0.208	0.0005	<.0006	0.0205	0.0269	10.4	<.0002	12.1	0.234

APPENDIX B (Continued)

Trace elements (in µg/L) in water collected in 2001 from coal bed methane (CBM) produced water discharges and receiving impoundments in the Powder River Basin, Wyoming.

Sample #		Mo	Ni	Pb	Se	Sr	V	Zn
Lynde								
CBMDLT1	Discharge	<.0044	<.00560	<.0111	<.00560	0.212	<.0044	<.0111
CBMWLT1	Wetland	<.0044	<.00560	<.0111	<.00560	0.25	0.0065	<.0111
Sorenson 3								
CBMDSOR3	Discharge	<.0044	<.00560	<.0111	<.00560	0.419	<.0044	<.0111
CBMWSR3A	Wetland	<.0044	<.00560	<.0111	<.00560	0.304	<.0044	<.0111
West								
CBMDWES1	Discharge	<.0044	<.00560	<.0111	<.00560	0.288	<.0044	<.0111
CBMWWES1	Wetland	0.0078	0.0143	0.0283	<.00560	5.26	<.0044	<.0111
Appel								
CBM001	Discharge	<1.00	0.50	0	0.12	1,150	<.010	4.30
CBMWAPR1	Wetland	<.0044	<.00560	<.0111	<.00560	0.262	<.0044	<.0111
Bower								
CBM003	Discharge	<1.00	2.2	0.13	0.09	335	<.0100	2.8
CBMWBOW1	Wetland	<.0044	0.0111	0.0144	<.00560	0.278	0.0228	0.0408

APPENDIX C

Trace elements (in µg/L), electrical conductivity (EC)(in µS/cm), and total dissolved solids (TDS) in coal bed methane (CBM) produced water collected from closed containment reservoirs and associated CBM discharges [DD-Lat = decimal degrees latitude][DD-Long = decimal degrees longitude].

Sheridan County/Tongue Watershed

Sample #	Site	DD-Lat	DD-Long	Al	As	B	Ba	Be	Ca	Cd	Cr	Cu	Fe	Hg
CBMCCR01	Reservoir	44.92594444	-106.8905556	1530	7.3	374	181	<0.5	33700	1.5	31.8	5.2	1160	<0
CBMCCRD1	Discharge	44.92594444	-106.8905556	847	3.3	182	322	<0.5	4130	1.4	4.9	4.3	875	<0
CBMCCR02	Reservoir	44.92013889	-106.8833056	3180	5.6	212	125	<0.5	7130	1.7	9.9	5.8	3070	<0
CBMCCRD2	Discharge	44.92013889	-106.8833056	1430	3	204	381	<0.5	4590	1.4	4.7	4.7	806	<0
CBMCCR03	Reservoir	44.91388889	-106.8820000	5300	7	217	155	<0.5	7570	2.2	13	7.7	4120	<0
CBMCCRD3	Discharge	44.91388889	-106.8820000	69.3	4.8	180	343	<0.5	4480	1.2	3	1.5	298	<0

Campbell County/Powder River Watershed

CBMCCR04	Reservoir	43.87100000	-105.8255556	1610	5.9	115	193	<0.5	14800	1.4	16.9	4.4	1350	<0
CBMCCRD4	Discharge	43.87100000	-105.8255556	8.2	2.8	98.6	687	<0.5	37500	1.1	15.7	2.3	376	<0

Sheridan County/Clear Creek Watershed

CBMCCR07	Reservoir	44.61983333	-106.3878333	451	2.3	208	204	<0.5	10400	1.2	9.5	2	507	<0
CBMCCRD7	Discharge	44.61983333	-106.3878333	3060	4	208	353	<0.5	11100	1.7	14.2	9.1	2920	<0
CBMCCR08	Reservoir	44.61825000	-106.3927500	495	3.1	266	312	<0.5	12300	1.2	11	1.5	412	<0
CBMCCRD8	Discharge	44.61825000	-106.3927500	517	<2	215	331	<0.5	10100	1.3	8.7	1.6	663	<0
CBMCCR09	Reservoir	44.62127778	-106.3788333	494	<2	132	40.8	<0.5	4280	2.5	9.3	4.2	428	<0

APPENDIX C (Continued)

Trace elements (in µg/L), electrical conductivity (EC)(in µS/cm), and total dissolved solids (TDS) in coal bed methane (CBM) produced water collected from closed containment reservoirs and associated CBM discharges [DD-Lat = decimal degrees latitude][DD-Long = decimal degrees longitude].

Sheridan County/Tongue Watershed

Sample #	Site	DD-Lat	DD-Long	Mg	Mn	Mo	Na	Ni	Pb	Se	Sr	V	Zn
CBMCCR01	Reservoir	44.92594444	-106.8905556	30900	74.5	2.2	197000	14.7	<5	6.9	478	3.7	5.9
CBMCCRD1	Discharge	44.92594444	-106.8905556	1720	9	1.7	466000	6.4	<5	3.5	187	1.2	4
CBMCCR02	Reservoir	44.92013889	-106.8833056	5060	46.7	<1	535000	7.8	<5	5.3	146	7.9	11.2
CBMCCRD2	Discharge	44.92013889	-106.8833056	1800	72.7	1.3	482000	10	<5	3.4	216	1.8	3.6
CBMCCR03	Reservoir	44.91388889	-106.8820000	5140	55.2	1	539000	9.9	<5.1	<2	153	12.9	19.4
CBMCCRD3	Discharge	44.91388889	-106.8820000	1800	4.8	<1	451000	3.7	<5.1	2.2	166	<1	4.7

Campbell County/Powder River Watershed

Sample #	Site	DD-Lat	DD-Long	Mg	Mn	Mo	Na	Ni	Pb	Se	Sr	V	Zn
CBMCCR04	Reservoir	43.87100000	-105.8255556	14500	78.4	<1	442000	8.6	<5.1	2.9	614	5	6.2
CBMCCRD4	Discharge	43.87100000	-105.8255556	11900	27	<1	380000	8.2	<5.1	3.2	1090	<1	2.6

Sheridan County/Clear Creek Watershed

CBMCCR07	Reservoir	44.61983333	-106.3878333	6950	7.6	<1	538000	6.1	<5.1	3.3	263	1.2	7.6
CBMCCRD7	Discharge	44.61983333	-106.3878333	7140	27.1	<1	564000	9.7	<5.1	3.9	302	6.1	60.2
CBMCCR08	Reservoir	44.61825000	-106.3927500	8440	7.7	<1	344000	6.1	<5.1	6.6	343	<1	6.3
CBMCCRD8	Discharge	44.61825000	-106.3927500	5870	9.8	<1	535000	5.6	<5.1	3.9	287	<1	4.7
CBMCCR09	Reservoir	44.62127778	-106.3788333	8950	7.2	1.5	463000	4.7	<5.1	8.4	139	1.6	5.2

APPENDIX C (Continued)

Trace elements (in µg/L), electrical conductivity (EC)(in µS/cm), and total dissolved solids (TDS) in coal bed methane (CBM) produced water collected from closed containment reservoirs and associated CBM discharges [DD-Lat = decimal degrees latitude][DD-Long = decimal degrees longitude].

Sheridan County/Tongue Watershed

Sample #	Site	DD-Lat	DD-Long	EC	TDS
CBMCCR01	Reservoir	44.92594444	-106.8905556	1960	980
CBMCCRD1	Discharge	44.92594444	-106.8905556	1765	909

CBMCCR02	Reservoir	44.92013889	-106.8833056	1940	985
CBMCCRD2	Discharge	44.92013889	-106.8833056	1899	953

CBMCCR03	Reservoir	44.91388889	-106.8820000	1970	1000
CBMCCRD3	Discharge	44.91388889	-106.8820000	1735	871

Campbell County/Powder River Watershed

Sample #	Site	DD-Lat	DD-Long	EC	TDS
CBMCCR04	Reservoir	43.87100000	-105.8255556	n.d.	n.d.
CBMCCRD4	Discharge	43.87100000	-105.8255556	n.d.	n.d.

Sheridan County/Clear Creek Watershed

CBMCCR07	Reservoir	44.61983333	-106.3878333	2100	1050
CBMCCRD7	Discharge	44.61983333	-106.3878333	1765	863
CBMCCR08	Reservoir	44.61825000	-106.3927500	2080	1050
CBMCCRD8	Discharge	44.61825000	-106.3927500	2100	1070
CBMCCR09	Reservoir	44.62127778	-106.3788333	1881	936

n.d. = not determined or not measured

APPENDIX D

Trace elements (in µg/g dry weight) in sediment collected in July 2001 from impoundments receiving coal bed methane (CBM) produced water discharges in the Powder River Basin, Wyoming.

Sample #	Al	As	B	Ba	Be	Cd	Cr	Cu
Appel								
CBMSAPR1	6299	5.81	13.5	155	0.761	0.695	14.7	18.7
CBMSAPR2	5227	6.25	11.3	158	0.56	0.6	11.8	13.4
CBMSAPR3	7513	13.1	15.6	119	0.864	0.934	16	20.7
CBMSAPR4	5427	4.61	11.8	137	0.734	0.789	13.9	17.7
CBMSAPR5	8258	7.83	13.1	140	0.795	0.843	15.2	18
Bower								
CBMSBOW1	14290	7.67	13.4	178	1.13	0.712	21.5	22.9
CBMSBOW2	14620	4.01	10.9	207	0.891	0.899	20.7	17.2
CBMSBOW3	9730	4.75	6.81	134	0.857	0.412	13.5	15.8
CBMSBOW4	8374	4.36	10.9	172	1.02	0.564	19.2	18.8
CBMSBOW5	10520	3.14	12.2	203	1.04	0.69	20.4	20.4
Little Thunder Reservoir								
CBMSLTR1	4109	1.57	12.3	115	0.333	0.303	6.47	7.21
CBMSLTR2	6197	2.83	10.5	103	0.459	0.46	9.13	10.3
CBMSLTR3	8074	2.42	13.1	128	0.594	0.603	9.46	12.9
CBMSLTR4	10280	1.94	12.3	143	0.656	0.607	12.7	13.2
CBMSLTR5	6140	2.33	15.5	116	0.462	0.401	8.15	9.3
Lynde								
CBMSLT1	6825	3.67	13.4	147	0.712	0.731	14.2	17.4
CBMSLT2	6934	3.41	10.9	109	0.542	0.527	12.1	10.6
CBMSLT3	8083	4.85	13.4	112	0.715	0.694	14.6	17.2
CBMSLT4	8485	5.07	14.7	141	0.774	0.839	15.4	19.6
CBMSLT5	3032	2.36	6.87	120	0.353	0.315	6.97	6.68
Sorenson 1								
CBMSSR1A	4080	3.61	11.4	82.4	0.442	0.405	8.07	9.36
CBMSSR1B	5744	5.42	12	150	0.438	0.453	8.07	14.3
CBMSSR1C	5702	4.08	11.6	96.2	0.555	0.529	9.5	14.9
CBMSSR1D	6660	4.94	9.83	65.5	0.398	0.42	9.8	14.3
CBMSSR1E	6373	4.73	12.2	52.1	0.506	0.534	9.26	16.3
Sorenson 2								
CBMSSR2A	10200	5.42	15.8	146	0.702	0.705	14.4	19
CBMSSR2B	7622	5.39	14.4	144	0.61	0.607	11.5	16.6
CBMSSR2C	7295	4.92	13.6	133	0.533	0.541	10.5	14.6
CBMSSR2D	9659	11.5	30.1	141	1.03	1.59	13.6	20.7
CBMSSR2E	11350	5.26	13.7	138	0.667	0.702	15	16.4
Sorenson 3								
CBMSSR3A	5272	2.63	9.12	238	0.577	0.459	11.5	10.7
CBMSSR3B	6643	4.59	11.5	380	0.655	0.627	15.5	13.5
CBMSSR3C	6341	6.62	16.7	324	0.79	0.82	14	12
CBMSSR3D	4917	5.84	6.47	146	0.44	0.266	16	5.59
CBMSSR3E	4739	5.25	11.8	250	0.579	0.75	15.6	23.8
West								
CBMSWES1	8267	4.32	13.1	333	0.78	0.879	13.9	16.2
CBMSWES2	9587	15.6	37.4	137	1.44	2.19	15.9	24
CBMSWES3	14210	11.7	31.1	134	1.59	2.26	18.1	22.3
CBMSWES4	7670	6.54	31.3	132	0.937	1.32	15.3	21.3
CBMSWES5	6792	4.65	20.4	120	0.864	1.28	15.8	19.4

APPENDIX D (Continued)

Trace elements (in µg/g dry weight) in sediment collected in July 2001 from impoundments receiving coal bed methane (CBM) produced water discharges in the Powder River Basin, Wyoming.

Sample #	Fe	Hg	Mg	Mn	Mo	Ni	Pb	Se
Appel								
CBMSAPR1	15120	<.0183	5106	232	<4.59	19.4	14.9	<.459
CBMSAPR2	14340	<.0191	4392	230	<4.77	14	12.5	<.477
CBMSAPR3	22220	<.0198	5138	229	<4.95	21.6	13.2	<.495
CBMSAPR4	14690	0.0213	5968	208	<4.60	18.1	13.2	<.460
CBMSAPR5	19360	<.0189	5798	326	<4.73	19.2	13.2	<.473
Bower								
CBMSBOW1	23060	0.0225	4616	397	<5.00	18.9	19.6	<.500
CBMSBOW2	17470	<.0182	4128	699	<4.55	21.7	18.1	<.455
CBMSBOW3	13420	<.0186	3556	173	<4.65	14.5	16.9	<.465
CBMSBOW4	12430	<.0197	4366	226	<4.92	16.8	18.6	<.492
CBMSBOW5	14680	<.0190	4871	287	<4.74	19.5	19.8	<.474
Little Thunder Reservoir								
CBMSLTR1	6026	<.0189	1163	103	<4.73	6.27	6.39	<.474
CBMSLTR2	8798	<.0191	1899	162	<4.77	9.43	9.18	<.477
CBMSLTR3	9730	<.0189	2996	238	<4.73	11.5	12.2	<.473
CBMSLTR4	9375	0.0195	2378	180	<4.84	11.4	14.1	<.484
CBMSLTR5	7789	<.0192	1688	145	<4.80	7.46	9.01	<.480
Lynde								
CBMSLT1	14600	<.0199	4269	229	<4.97	17.5	13.3	<.497
CBMSLT2	12740	<.0191	4297	280	<4.77	12.6	10.7	<.477
CBMSLT3	15010	<.0187	4843	226	<4.67	17.5	12.8	0.61
CBMSLT4	16050	<.0196	4944	277	<4.89	19.2	15.6	0.62
CBMSLT5	8203	<.0185	2817	131	<4.63	8.27	6.56	<.463
Sorenson 1								
CBMSSR1A	9384	<.0193	1685	175	<4.83	10.5	7.04	<.483
CBMSSR1B	17000	<.0198	10060	446	<4.95	10.2	7.52	<.495
CBMSSR1C	13050	0.0194	4736	248	<4.82	12.6	9.61	<.482
CBMSSR1D	14030	<.0196	12500	365	<4.90	11	8.8	<.490
CBMSSR1E	18230	<.0195	13550	614	<4.87	8.36	7.04	<.487
Sorenson 2								
CBMSSR2A	16340	0.0236	5036	343	<4.80	14.9	12.7	<.480
CBMSSR2B	14030	0.0209	5342	313	<4.73	13.4	10.9	<.474
CBMSSR2C	13470	0.0201	5580	339	<4.85	12.4	10.4	<.485
CBMSSR2D	47880	0.0208	5649	693	<4.88	15.7	8.12	<.488
CBMSSR2E	15410	<.0194	4295	329	<4.85	13.7	13.3	<.485
Sorenson 3								
CBMSSR3A	9848	<.0191	3651	201	5.99	11.6	10.9	<.478
CBMSSR3B	15630	0.0198	4496	289	8.1	16.2	12.2	<.473
CBMSSR3C	28220	<.0186	3981	428	5.56	14	6.4	<.466
CBMSSR3D	10650	<.0186	3057	104	<4.64	9.06	7.68	<.464
CBMSSR3E	16320	0.0227	4478	305	<4.60	24.4	18.4	<.460
West								
CBMSWES1	20890	<.0186	3500	821	<4.64	16.9	12.3	0.91
CBMSWES2	39500	0.0386	10440	2924	<4.84	38.5	12.7	1.34
CBMSWES3	24140	0.041	11530	1506	<4.80	42	16.6	1.68
CBMSWES4	24270	0.0339	8613	1349	<4.79	26.9	13.6	1.1
CBMSWES5	14680	0.0282	5474	436	<4.60	20.8	15.1	<.460

APPENDIX D (Continued)

Trace elements (in µg/g dry weight) in sediment collected in July 2001 from impoundments receiving coal bed methane (CBM) produced water discharges in the Powder River Basin, Wyoming.

Sample #	Sr	V	Zn
Appel			
CBMSAPR1	78.2	23.8	64
CBMSAPR2	61.5	19.4	57.2
CBMSAPR3	49.8	26.9	78.5
CBMSAPR4	74.3	21.1	64.3
CBMSAPR5	66.4	24.7	67.7
Bower			
CBMSBOW1	75.5	32.3	75.9
CBMSBOW2	68	30.9	63.1
CBMSBOW3	57.9	15.1	55.8
CBMSBOW4	71	31.5	66.2
CBMSBOW5	74	32.3	75
Little Thunder Reservoir			
CBMSLTR1	31.2	13	22.4
CBMSLTR2	30.5	19.6	31.3
CBMSLTR3	78.8	17.2	43.3
CBMSLTR4	53.3	20.9	47.7
CBMSLTR5	49.5	16.9	30.4
Lynde			
CBMSLT1	71.6	24.2	61.3
CBMSLT2	65.9	14.9	46.6
CBMSLT3	57.9	23	57.1
CBMSLT4	70.5	24.6	66.8
CBMSLT5	34.2	10.1	29.6
Sorenson 1			
CBMSSR1A	26.6	13.6	28
CBMSSR1B	45.8	13	33.5
CBMSSR1C	36.9	15.6	43.5
CBMSSR1D	43.8	14.2	33.9
CBMSSR1E	64.1	16.1	33.1
Sorenson 2			
CBMSSR2A	102	20.4	49.5
CBMSSR2B	106	18.8	42
CBMSSR2C	115	17	41.2
CBMSSR2D	89.9	25.6	55.6
CBMSSR2E	65.6	24.2	46
Sorenson 3			
CBMSSR3A	107	17.8	38
CBMSSR3B	155	20.4	52.7
CBMSSR3C	122	34.7	47.4
CBMSSR3D	53.4	13.8	33.4
CBMSSR3E	89.6	20.5	58.3
West			
CBMSWES1	124	18.1	67.2
CBMSWES2	195	32.8	113
CBMSWES3	179	31.5	153
CBMSWES4	119	29	85.8
CBMSWES5	81.9	25.5	78.7

APPENDIX E

Trace elements (in µg/g dry weight) in aquatic vegetation collected in July 2001 from impoundments receiving coal bed methane (CBM) produced water discharges in the Powder River Basin, Wyoming.

Watermilfoil

Sample #	Al	As	B	Ba	Be	Cd	Cr	Cu	Fe	Hg	Mg
Appel											
CBMVAPR1	1779	2.68	49.2	334	<.0928	<.0928	3.3	4.03	1297	<.0186	5543
CBMVAPR2	793	1.24	33.1	358	<.0952	<.0952	2.47	3.91	617	<.0190	6939
CBMVAPR3	845	1.3	37.6	380	<.0971	<.0971	2.91	5.36	688	<.0194	7251
CBMVAPR4	1029	1.17	34.4	374	<.0933	<.0933	3.33	5.28	812	<.0187	7530
CBMVAPR5	1682	1.59	34.5	355	<.0965	<.0965	3.19	4.63	1277	<.0193	6454

Pondweed

Sample #	Al	As	B	Ba	Be	Cd	Cr	Cu	Fe	Hg	Mg
Bowers											
CBMVBOW1	3513	2.72	362	391	<.0911	0.322	56.1	11.4	2157	0.0205	9199
CBMVBOW2	6532	2.22	299	267	<.0914	0.244	32	9.4	3673	0.0186	6681
CBMVBOW3	9727	2.34	221	433	<.0960	0.747	19	9.35	5286	<.0192	7514
CBMVBOW4	7567	2.23	337	494	<.0942	0.469	12.5	8.4	3913	<.0188	7566
CBMVBOW5	7183	3.54	282	832	<.0943	0.337	11	7.52	3759	<.0189	8387
Little Thunder Reservoir											
CBMVLTR1	1230	2.36	384	1055	<.0305	0.914	1.37	2.65	1154	<.0509	6970
CBMVLTR2	2350	3.3	396	498	<.0304	1.33	2.72	2.93	2027	<.0507	7081
CBMVLTR3	1059	2.2	322	532	<.0305	0.839	1.18	2.91	1088	<.0509	6889
CBMVLTR4	1445	2.61	267	520	<.0296	1.04	1.63	3.13	1207	<.0494	7481
CBMVLTR5	1684	2.55	251	630	<.0304	1.19	1.57	4.12	1288	<.0507	8232
Lynde											
CBMVLT1	664	1.82	136	130	<.0945	<.0945	4.26	4.12	478	0.0292	4151
CBMVLT2	1021	3.05	207	145	<.0971	<.0971	7.61	4.85	1534	0.0537	4648
CBMVLT3	902	1.46	46.9	110	<.0954	<.0954	7.44	4.01	787	0.0273	4081
CBMVLT4	930	2.51	41.3	88.1	<.0935	<.0935	5.77	5.2	690	0.036	5199
CBMVLT5	2233	3.7	115	103	<.0952	<.0952	9.56	4.96	1608	0.04	5863
Sorenson 3											
CBMVSR3A	2729	1.25	21.5	1042	<.0965	<.0965	11.7	7.4	1942	0.0207	3861
CBMVSR3B	2324	0.78	19.7	978	<.0982	<.0982	7.46	6.59	1852	0.0217	4007
CBMVSR3C	3149	1.18	20.3	994	<.0936	<.0936	8.89	6.46	2232	<.0187	4020
CBMVSR3D	3024	1.07	18.2	984	<.0947	<.0947	7.3	6.5	1967	0.0199	3873
CBMVSR3E	3212	0.92	18.3	900	<.0988	<.0988	6.72	6.03	1853	0.0205	3889
West											
CBMVWES1	11822	3.06	159	1007	0.231	0.799	15.8	7.58	7492	<.0187	4939
CBMVWES2	8361	2.84	155	1039	0.16	0.565	11.3	6.62	5707	<.0192	4695
CBMVWES3	9764	2.76	208	1215	0.117	0.438	12.2	6.3	5538	<.0198	5684
CBMVWES4	12810	3.46	164	992	0.177	0.642	15.1	6.85	6766	0.0201	5200
CBMVWES5	9947	2.79	174	870	0.133	0.527	14.4	6.55	5781	<.0186	4889

APPENDIX E (Continued)

Trace elements (in µg/g dry weight) in aquatic vegetation collected in July 2001 from impoundments receiving coal bed methane (CBM) produced water discharges in the Powder River Basin, Wyoming.

Watermilfoil

Sample #	Mn	Mo	Ni	Pb	Se	Sr	V	Zn
Appel								
CBMVAPR1	374	2.4	4.93	<.928	<.464	416	<.464	21.4
CBMVAPR2	165	4.63	4.73	<.952	<.476	397	<.476	20.4
CBMVAPR3	201	7.14	4.87	<.971	0.81	470	<.485	26.3
CBMVAPR4	186	3.9	4.95	<.933	0.56	437	<.466	26.4
CBMVAPR5	192	8.54	5.63	<.965	<.483	425	<.483	20.3

Pondweed

Sample #	Mn	Mo	Ni	Pb	Se	Sr	V	Zn
Bowers								
CBMVBOW1	132	8.29	16.9	<.911	0.58	646	6.38	72.7
CBMVBOW2	207	9.39	14.5	<.914	0.86	375	7.98	115
CBMVBOW3	280	4.46	10.8	<.960	0.5	570	12.5	66.5
CBMVBOW4	261	12.6	8.67	<.942	0.62	617	8.91	52
CBMVBOW5	533	2.88	8.52	<.943	<.472	946	7.63	65.2
Little Thunder Reservoir								
CBMVLTR1	722	<1.02	3.04	<.509	1.3	407	3.8	17.1
CBMVLTR2	668	<1.01	2.79	<.507	1.07	394	7.13	18
CBMVLTR3	701	<1.02	1.97	<.509	0.801	333	3.87	17.6
CBMVLTR4	1148	<.988	1.95	<.494	2.33	548	5.06	26.7
CBMVLTR5	541	<1.01	1.94	<.507	1.86	758	4.98	24.5
Lynde								
CBMVLT1	213	0.892	6.62	<.945	<.473	189	<.473	42.3
CBMVLT2	590	<.485	8.87	<.971	0.57	242	<.485	87.9
CBMVLT3	182	1.34	8.75	<.954	0.67	174	<.477	37.8
CBMVLT4	160	1.18	7.78	<.935	<.467	175	<.467	51.1
CBMVLT5	246	0.481	9.42	<.952	<.476	176	<.476	30.7
Sorenson 3								
CBMVSR3A	129	1.91	13.9	<.965	<.483	426	2.66	44.3
CBMVSR3B	96.8	1.67	12.1	<.982	<.491	417	2.26	40.9
CBMVSR3C	115	1.36	11.9	<.936	<.468	409	2.52	36.3
CBMVSR3D	103	1.28	10.7	<.947	<.474	414	2.47	42
CBMVSR3E	164	1.25	11.9	<.988	0.65	358	2.02	46.8
West								
CBMVWES1	906	<.466	11.7	<.933	0.61	541	7.73	51.7
CBMVWES2	968	<.480	10.5	<.960	0.52	569	2.39	65.2
CBMVWES3	847	<.494	9.66	<.988	<.494	686	3.9	111
CBMVWES4	713	<.474	11.1	<.949	<.474	552	8.28	54.6
CBMVWES5	603	<.465	11	<.929	<.465	479	6.74	49.9

APPENDIX F

Trace elements (in µg/g dry weight) in aquatic invertebrates collected in July 2001 from impoundments receiving coal bed methane (CBM) produced water discharges in the Powder River Basin, Wyoming.

Odonates

Sample #	Al	As	B	Ba	Be	Cd	Cr	Cu	Fe	Hg	Mg
Appel											
CBMIAPR4	162	0.63	7.96	27	<.0917	0.393	<.459	13.5	257	0.193	1390
CBMIAPR5	315	0.89	9.8	28.3	<.0917	0.567	<.459	14.7	402	0.237	1656

Backswimmers

Appel	Al	As	B	Ba	Be	Cd	Cr	Cu	Fe	Hg	Mg
CBMIAPR1	41.2	<.740	30.4	10.4	<.148	0.551	<.740	19.2	127	0.206	2388
CBMIAPR2	178	<.494	9.07	25	<.0988	0.84	<.494	7.86	296	0.109	1866
CBMIAPR3	213	<.483	12.8	33.3	<.0965	1.06	<.483	10.5	332	0.184	2762
Bowers											
CBMIBOW1	246	1.64	24.4	15.1	<.0998	2.15	<.499	20.8	255	0.254	2471
CBMIBOW2	647	1.66	13.9	29.7	<.0956	3.26	0.937	29.4	630	0.184	2132
CBMIBOW3	302	1.31	8.76	16.9	<.0909	2.26	<.454	21.2	267	0.263	2584
CBMIBOW5	170	1	9.93	14.3	<.0960	2.12	<.480	20.5	203	0.261	2568
CBMIBOW6	279	1.31	8.7	19.7	<.0960	3.1	<.480	14	437	0.195	2521

Waterboatmen

Lynde	Al	As	B	Ba	Be	Cd	Cr	Cu	Fe	Hg	Mg
CBMILT1	301	<1.33	98.6	8.78	<.266	<.266	<1.33	16.1	291	0.282	1335
Sorenson 3											
CBMISR3A	134	0.82	22	27.8	<.0975	1.45	<.487	25.6	226	0.456	2092
CBMISR3B	147	1	28.9	28.9	<.109	1.74	<.544	25.7	216	0.48	2093
CBMISR3C	141	<.886	75.7	27.4	<.177	1.3	<.886	26.2	200	0.367	2070

Odonates

Appel	Mn	Mo	Ni	Pb	Se	Sr	V	Zn
CBMIAPR4	28.1	<.459	1.02	<.917	<.459	23.1	<.459	128
CBMIAPR5	30.8	<.459	0.922	<.917	<.459	30.1	0.519	134

Backswimmers

Appel	Mn	Mo	Ni	Pb	Se	Sr	V	Zn
CBMIAPR1	36.3	<.740	<.740	<1.48	<.740	26.4	<.740	144
CBMIAPR2	32	<.494	1.07	<.988	<.494	70.7	<.494	105
CBMIAPR3	45	<.483	0.809	<.965	<.483	86.5	0.774	149
Bowers								
CBMIBOW1	29.8	<.499	0.669	<.998	<.499	24.3	<.499	159
CBMIBOW2	39.3	<.478	1.54	<.956	<.478	38.8	0.928	170
CBMIBOW3	31.6	<.454	0.574	<.909	<.454	24.8	<.454	165
CBMIBOW5	28.8	<.480	0.568	<.960	<.480	23.9	<.480	168
CBMIBOW6	29.9	<.480	0.634	<.960	<.480	32.2	0.67	185

Waterboatmen

Lynde	Mn	Mo	Ni	Pb	Se	Sr	V	Zn
CBMILT1	24.1	<1.33	1.87	<2.66	<1.33	13.4	<1.33	174
Sorenson 3								
CBMISR3A	28.3	<.487	0.743	<.975	2.2	46.7	<.487	190
CBMISR3B	26.5	<.544	0.839	<1.09	2.24	43.1	<.544	187
CBMISR3C	28.4	<.886	4.38	<1.77	<.886	39	1.95	195

APPENDIX G

Trace elements (in µg/g dry weight) in tiger salamanders collected in July 2001 from impoundments receiving coal bed methane (CBM) produced water discharges in the Powder River Basin, Wyoming.

Sample #	Al	As	B	Ba	Be	Cd	Cr	Cu	Fe	Hg	Mg
Appel											
CBMAAPR1	892	<.718	<2.87	33.5	<.144	0.364	25.6	5.89	796	0.0942	1622
CBMAAPR2	573	<.729	<2.92	24.6	<.146	0.367	18.6	5.92	519	0.0715	1578
CBMAAPR3	1468	<.814	<3.26	34.3	<.163	0.677	36.1	4.57	1104	0.0829	1710
CBMAAPR4	652	<.804	<3.22	36.6	<.161	0.443	46.9	6.16	676	0.0805	1774
CBMAAPR5	607	<.794	<3.17	30.6	<.159	0.487	64.9	5.25	847	0.0669	1395
Bowers											
CBMABOW1	1086	<.764	<3.06	41.6	<.153	0.541	22.8	5.72	827	0.0796	1609
CBMABOW2	2806	2.69	<3.23	41.5	<.161	1.24	24.7	6.03	1658	0.126	1722
CBMABOW3	1131	<.751	7.36	49.8	<.150	0.869	104	7.35	1267	0.108	1726
CBMABOW4	1588	<1.30	<5.18	57.9	<.259	0.818	19.2	5.56	924	0.103	1656
CBMABOW5	1721	<.825	<3.30	44.2	<.165	0.88	59.6	6.09	1135	0.108	1843
Sorenson 3											
CBMASR3A	1056	<.718	<2.87	120	<.144	0.513	26.6	6.54	987	0.207	1661
CBMASR3B	923	<.748	<2.99	138	<.150	0.723	23.8	7.41	1275	0.321	1720
CBMASR3C	2918	<.760	<3.04	131	<.152	1.31	36.8	6.8	2243	0.194	1896
CBMASR3D	2095	2.21	<2.99	126	<.150	2.84	76.3	4.98	6918	0.186	1502
CBMASR3E	3914	<.738	3.1	111	<.148	1.39	137	7.34	3054	0.228	1707

Appel	Mn	Mo	Ni	Pb	Se	Sr	V	Zn
CBMAAPR1	18.1	<.718	9.31	<1.44	<.718	131	1.4	87.7
CBMAAPR2	9.82	<.729	8.47	<1.46	<.729	135	<.729	151
CBMAAPR3	16.2	<.814	14.2	<1.63	<.814	174	2.32	157
CBMAAPR4	19.4	<.804	17.3	<1.61	<.804	164	0.956	201
CBMAAPR5	20.8	1.07	21.8	<1.59	<.794	116	1.14	181
Bowers								
CBMABOW1	14.7	<.764	9.61	<1.53	<.764	144	1.26	89.4
CBMABOW2	18.5	<.806	11.8	<1.61	<.806	144	3.52	98.7
CBMABOW3	35.7	1.7	29	<1.50	<.751	140	1.84	125
CBMABOW4	30.7	<1.30	9.64	<2.59	<1.30	186	2.23	122
CBMABOW5	26.4	<.825	20.8	<1.65	2.18	172	2.44	102
Sorenson 3								
CBMASR3A	17.7	1.05	7.98	<1.44	<.718	157	1.51	121
CBMASR3B	23.4	<.748	5.98	<1.50	1.95	189	1.48	122
CBMASR3C	36.1	1.32	13.1	<1.52	<.760	174	4.92	122
CBMASR3D	91.8	1.77	26.3	<1.50	<.748	118	12.7	85
CBMASR3E	50.4	2.18	34.8	<1.47	<.738	130	5.82	118

APPENDIX H

Trace elements (in µg/g dry weight) in whole-body fish collected in July 2001 from two impoundments receiving coal bed methane (CBM) produced water discharges in the Powder River Basin, Wyoming.

Little Thunder Reservoir

Black Bulhead

Sample #	Al	B	Ba	Cd	Cr	Cu	Fe	Hg	Mg	Mn	Mo
CBMFLTR1	749	2.45	56.9	0.119	0.741	3.05	421	0.119	1851	21.4	<1.00
CBMFLTR2	161	1.65	54.6	<.0973	0.331	2.56	160	0.121	1922	21.7	<.973
CBMFLTR3	146	0.794	39	<.100	<0.1	2.74	148	0.137	1843	15.4	<1.00
CBMFLTR4	193	<0.496	50	<.0992	0.217	3.1	168	0.142	2004	14.3	<.992
CBMFLTR5	81.8	<0.514	50.6	<.103	0.136	3.12	127	0.16	2243	17.8	<1.03

Lynde

Fathead Minnow

Sample #	Al	B	Ba	Cd	Cr	Cu	Fe	Hg	Mg	Mn	Mo
CBMFLT1	139	<3.31	28.8	0.883	307	6.71	2173	0.182	1570	32.7	5.47
CBMFLT2	182	<3.19	53.5	0.288	98.3	4.76	888	0.194	2168	18	1.72
CBMFLT3	843	<3.02	52.4	0.671	213	7.48	1725	0.197	2250	35	4.07
CBMFLT4	241	<2.98	36.9	0.151	24.4	4.15	344	0.296	2187	14.5	<0.744
CBMFLT5	264	<3.18	55	0.354	111	5.75	845	0.306	2281	24.8	1.74

Little Thunder Reservoir

Black Bulhead

Sample #	Ni	Pb	Se	Sr	V	Zn
CBMFLTR1	<.100	<.502	3.6	327	0.72	118
CBMFLTR2	<.0973	<.486	2.25	342	<.0973	148
CBMFLTR3	<.100	<.500	2.61	275	<.100	178
CBMFLTR4	<.0992	<.496	4.36	345	<.0992	135
CBMFLTR5	<.103	<.514	2.61	334	<.103	167

Lynde

Fathead Minnow

Sample #	Ni	Pb	Se	Sr	V	Zn
CBMFLT1	113	<1.66	3.92	118	2.42	225
CBMFLT2	29.9	<1.60	2.28	214	1.26	270
CBMFLT3	46.8	36.5	2.59	180	2.7	252
CBMFLT4	10.4	<1.49	<0.744	208	0.846	235
CBMFLT5	30.9	<1.59	4.36	214	1.23	190