The Effects of Coalbed Natural Gas Activities on Fish Assemblages: A Review of the Literature

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Executive Summary

Effects of coalbed natural gas (CBNG) development on fish assemblages in the Powder River Basin are generally unknown. Fishes endemic to the Powder River Basin have evolved life history strategies that allow them to survive in extreme conditions. However, water development that alters water quality or water quantity may nevertheless result in changes in the fish assemblage. Few studies have been conducted to specifically address the effects of CBNG development on fish assemblages in the Powder River Basin, but studies conducted elsewhere have addressed changes in water quality and water quantity, and surface environment alterations such as road building. We reviewed the literature pertaining to these potential effects and considered the applicability of these studies to CBNG development. However, CBNG development in the Powder River Basin is unique because product water in other basins is not typically discharged to surface waters.

An exception is the Black Warrior Basin, Alabama, where no significant decline in fish species diversity or total fish biomass occurred after discharge of CBNG product water began. However, the abundance of Gulf darters (*Etheostoma swaini*) decreased with the presence of product water, and reproduction of the rough shiner (*Notropis baileyi*) was significantly greater downstream of discharge. These subtle patterns of fish species variation suggested that the aquatic system was changing and that long periods of CBNG product water discharge may result in changes in assemblage composition.

The inferences that can be made among geologic basins with CBNG development are limited because the major ion composition of product water varies among basins. Moreover, CBNG product water can be variable within a geologic basin. In the Powder River Basin, CBNG product water is highly variable among wells and chemistry changes as it mixes with surface waters and equilibrates with the atmosphere.

Information on chronic toxicity of saline discharges on fish in the Powder River Basin is generally lacking, presenting a substantial gap in predicting effects. Hatch and survival rates of fathead minnow eggs exposed to sodium bicarbonate ($NaHCO_3$), the major salt associated with

CBNG product water in the Powder River Basin, were lower than controls in both acute and chronic exposures. However, use of the fathead minnow, a species tolerant to adverse biological conditions, including a high salinity tolerance, likely underestimates the potential effects to more sensitive native species. Although water quality standards for total dissolved solids (TDS) and conductivity are established by the Montana and Wyoming departments of environmental quality to protect aquatic life, general parameters such as TDS and conductivity do not account for the differing toxicities of individual ions or combinations of ions. Instream acute and chronic toxicity tests with native fish species of various tolerance levels should be conducted to better understand the effects of CBNG product water to fish assemblages in the field.

The effects that other water quality parameters may have on fish assemblages in the Powder River Basin are uncertain. Reported pH levels of CBNG product water are within the optimal range for fish productivity. Metals may be a concern, because the levels of several metals and trace elements in CBNG product water, wetlands, impoundments, sediments and biological tissues exceeded either Wyoming Department of Environmental Quality chronic standards or other biologically relevant thresholds. CBNG product water is low in dissolved oxygen, but no information exists on the potential for CBNG discharges to change instream dissolved oxygen levels. No information is available on the turbidity levels of CBNG product water, but the authors have noted product water can be less or more turbid than surface water. If CBNG product water reduces turbidity, non-native sight feeding fish may be afforded a competitive advantage over native fish. Increased turbidity may also alter native fish assemblages.

Coalbed natural gas development may change natural stream flow and temperature regimes in the Powder River Basin where intermittent or ephemeral surface water discharges are typical. The pumping of coal seam aquifers may lead to the reduction of water inputs from springs and hyphorheic flow that help maintain important refugia for fish. Conversely, discharge of CBNG product water to streams increases stream discharge in some areas. The temperature of CBNG product water is within the range of temperatures found in surface waters in the Powder River Basin, but is relatively constant year-round. Continuous input of constant-temperature product water may disrupt natural environmental cues and result in changes in fish behavior and reproduction.

Road construction associated with CBNG development may increase stream sedimentation and constructed stream crossings may fragment fish populations and lead to decreased diversity. Whereas some streams of the Powder River Basin have naturally high sediment loads, others have rocky substrate and provide important spawning habitat for migratory fish. Increased sedimentation of these streams may lead to the elimination of reproductive opportunities for litho-obligate species such as goldeye (*Hiodon alosoides*), sturgeon chub (*Macrhybopsis gelida*), longnose dace (*Rhinichthys cataractae*), and sand shiner (*Notropis stramineus*).

Uncertainty exists concerning the potential effects of CBNG development on fish in the Powder River Basin. The severity and direction of effects that are known are ambiguous because of differing environmental conditions and spatial and temporal differences in product and surface water chemistry among geologic basins and within the Powder River Basin. This highlights the need for further field and laboratory research. Field-based research, including baseline biomonitoring and directed field studies will be beneficial because stream biota are indicators of instream environmental conditions. Directed field studies in drainages with and without CBNG development, upstream and downstream of CBNG development, and before and after CBNG development are needed to ascertain if CBNG development has affected fish assemblages. Laboratory and instream acute and chronic toxicity tests with native fish species should be conducted to better understand the effects of CBNG product water on fish.

Physical Setting of the Powder River Basin

Geology

In geologic terms, the Powder River Basin (PRB) is a structural basin characterized by Cenozoic sediments of continental origin (Brown 1993) that formed during the Laramie Orogeny about 60 million years ago (Alt and Hyndman 1986; Glass and Blackstone 1996). The PRB is bounded by the Bighorn Mountains on the west, the Black Hills on the east, and extends north from near Douglas, Wyoming, to Miles City, Montana. The PRB is about 31,000 km^2 in area (Ellis et al. 1999), extending about 354 km from north to south and up to about 153 km from east to west, with about two-thirds of its area in Wyoming and one-third in Montana.

The PRB is rich in energy resources including oil, gas, and coal deposits. It contains some of the world's largest deposits of low-sulfur bituminous coal, most of which is federally owned (BLM 2003). The most important coal seams in the PRB are associated with the Fort Union and Wasatch Formations where coalbed natural gas (CBNG) retention is enhanced by the hydrostatic pressure of groundwater within the coal seam. The recoverable CBNG resource has been estimated at 24 to 39 trillion cubic feet, of which less than one trillion cubic feet occurs in Montana (Decker 2001; BLM 2003; Ruckelshaus Institute of Environment and Natural Resources 2005). The relatively small amount of CBNG in Montana reflects less favorable geologic structure and topography for CBNG production, as well as the smaller area of the PRB in Montana (Wheaton and Donato 2004a).

Physiography

The PRB is located in the Northwestern Great Plains ecoregion (Woods et al. 2002; Chapman et al. 2004). It was unglaciated. Elevations of the PRB range from about 2,200 m in the foothills of the Bighorn Mountain in Wyoming to 719 m at the mouth of the Tongue River in Montana. The region has a semiarid continental climate with annual precipitation ranging from 30 to 48 cm, and mean annual frost free-days ranging from 90 to 135 days. Mean monthly minimum and maximum January air temperatures are -19º C and 2º C, whereas mean monthly minimum and maximum July air temperatures are 10º C and 32º C.

A wide range of vegetative types exist in the PRB, ranging from grasslands with grama, needlegrass, and wheatgrass, to shrubs including rabbitbrush, fringed sage, and snowberry, to Rocky Mountain juniper-ponderosa pine forests in the pine scoria hills. Riparian areas often contain deciduous woody vegetation including cottonwood, boxelder, and chokecherry. Land use in the PRB is primarily rangeland grazing, with dryland agriculture and limited irrigated and sub-irrigated agriculture along the major stream valleys. Coal mining, coalbed natural gas production, oil production, and uranium mining are localized land uses in the PRB (Woods et al. 2002; Chapman et al. 2004).

Hydrology

Surface water.—The PRB contains portions of several surface hydrologic basins including most of the Tongue and Powder rivers, the upper portions of the Belle Fourche and Cheyenne rivers, Rosebud and Armells creeks in Montana, and a small portion of the North Platte River. All of the surface waters of the PRB are within the Missouri River basin. The Tongue and Powder rivers and Rosebud and Armells creeks are north-flowing tributaries of the Yellowstone River. The Belle Fourche River is a tributary of the Cheyenne River, which joins the Missouri River at Lake Oahe Reservoir in South Dakota. The North Platte River and the South Platte River form the Platte River in Nebraska, which joins the Missouri River south of Omaha, Nebraska.

Streams of the PRB have headwaters in either montane or plains regions. Although each stream has unique topography, geology, vegetative cover, and drainage basin area, some generalizations can be made in distinguishing streams of the PRB with montane headwaters from those of plains origin (Clark et al. 2001; BLM 2003). Streams with montane headwaters have stream flows that are dominated by snowmelt (Lowham 1988), have lower temperatures and concentrations of dissolved and suspended solids (but which increase downstream as they traverse the plains), and more perennial flows than plains streams (BLM 2003). In contrast, plains streams tend to be ephemeral, containing water only after rains or snowmelt (Lowham 1988), or intermittent, with flow in response to rain or snowmelt, but maintaining isolated pools year-round. Only the largest plains streams approach conditions of perennial flow. Plains rivers and streams have highly variable hydrographs, as illustrated by the Powder River, which had an estimated peak discharge of 100,000 cfs at Moorhead, Montana, in 1923 (USGS 2005a), but also has 146 days on record when streamflow was 0 or less than 1 cfs (USGS 2005b).

The headwaters of the Tongue River are in the Bighorn Mountains west of Sheridan, Wyoming. The river then flows generally northeast to meet the Yellowstone River at Miles City, Montana. The Tongue River Dam forms the 1,416 ha (at full pool) Tongue River Reservoir near Decker, Montana, and regulates the downstream hydrograph and thermograph. Additionally, four lowhead irrigation diversion dams are located on the Tongue River between the Tongue River Dam and the confluence with the Yellowstone River. The Tongue River drainage basin area is 13,932 km^2, 70% of which is in Montana (Elser et al. 1980). In Wyoming, perennial tributaries of the Tongue River include Goose Creek, Prairie Dog Creek, and Youngs Creek (Wesche and Johnson 1981). The largest tributaries in Montana are Hanging Woman, Otter, and Pumpkin creeks; these three plains tributaries lack discharge data but are likely intermittent.

The Powder River is the largest hydrologic basin in the PRB; its drainage basin area is 34,318 km^2 (Rehwinkle 1978). The North Fork of the Powder River originates in the Bighorn Mountains in Wyoming, the Middle Fork originates in the Wyoming basin ecoregion (Chapman et al. 2004), and the South Fork originates on the northwestern Great Plains near Powder River, Wyoming. The Powder River is recognized as perhaps the most pristine remaining example of a Great Plains river and is characterized by its high turbidity, salinity, flashy hydrograph, shallow water depths, and shifting sand substrate (Rehwinkle 1978; Elser et al. 1980; Hubert 1993). Only four perennial tributaries enter the Powder River–Crazy Woman Creek and Clear Creek in Wyoming and the Little Powder River and Mizpah Creek in Montana (Hubert 1993).

Groundwater.—Groundwater resources are found in several aquifers that are located at varying depths below the land surface in the PRB. Aquifers that occur at or near the land surface are associated with alluvial or basin fill deposits, sandstones, coal beds, or clinker (Whitehead 1996; Heffern and Coates 1999). Groundwater flows generally northward in the PRB and springs that discharge ground water are commonly found where coal seams crop out in the Montana portion of the PRB (Wheaton and Donato 2004a). Groundwater associated with coal seams is generally suitable for drinking and livestock water (Wheaton and Donato 2004a).

Deeply buried aquifers in the PRB are geologically older and isolated from the shallow aquifers, and are too deep to be affected by CBNG development (BLM 2003). The chemistry of groundwater changes with depth. Calcium (Ca^{2+}), magnesium (Mg^{2+}), and sulfate (SO_4^{2-}) decrease, whereas bicarbonate (HCO_3^-) increases with depth to about 152 m. Below 152 m deep, the water chemistry is more static, and sodium (Na^+) and bicarbonate are the dominant ions (Rankl and Lowry 1990; BLM 2003a). The water quality of water co-produced by traditional oil and gas activities from deep aquifers is so poor that surface disposal is normally not permitted (Wheaton and Donato 2004a).

Fish of the Tongue and Powder Rivers

The Great Plains region was likely drained by three major river systems prior to Pleistocene glaciations: an Arctic river that flowed to Hudson Bay (today's upper Missouri River), the southward flowing Mississippi river system, and a preglacial Plains river that also drained southward, but largely independent of the preglacial Mississippi. Southward advances of glacial ice deflected the northward- and eastward-flowing drainages to the south and contributed glacial runoff. Thus, glacial advances created the contemporary Missouri/Mississippi drainage pattern and allowed mingling of the ichthyofaunas of the three preglacial drainage basins (Cross et al. 1986).

Currently, 30 native and 22 introduced fish species representing 13 families occur in the Powder and Tongue river basins (Brown 1971; Baxter and Stone 1995; Holton and Johnson 2003; Table 1). Cyprinids (minnows) are most speciose, with 11 native and 3 introduced species, followed by catostomids (suckers) with 8 native species.

The primary aquatic habitats of this area are the Powder and Tongue rivers, large plains streams, small plains streams, and cold water habitats. The Yellowstone River has a fairly diverse fish assemblage of 56 species (White and Bramblett 1993) and because it is connected to the Powder and Tongue rivers, provides a link to large river habitats for many species including pallid and shovelnose sturgeon, blue sucker, and sauger (Table 1). The ichthyofaunas of the

Powder and Tongue rivers have at least 13 species in common, but introduced species are much more common in the Tongue River (Table 1). The Tongue River has about 16 introduced species that do not occur, or rarely occur, in the Powder River. This is because of the altered habitat conditions and the increased probability of species introductions associated with the Tongue River Reservoir and the cool, clear hypolimnetic water released from the Tongue River Dam. In contrast, only two introduced species commonly occur in the Powder River (common carp and plains killifish); both species are tolerant of environmental extremes (Bramblett et al. 2005). Two native species that are adapted to naturally turbid plains rivers, shovelnose sturgeon and sturgeon chub, are found in the Powder River and not in the Tongue River. The ichthyofauna of large plains streams (e.g., Hanging Woman Creek, Otter Creek, Little Powder River) is similar to the ichthyofauna of smaller plains streams except that fewer species are found in the small plains streams (Table 1). Brook stickleback are the only species found primarily in small plains streams and not in large plains streams (Table 1; Bramblett, unpublished data). Fishes found in cold water habitats occur in streams of montane origin or immediately downstream of Tongue River Dam.

A total of nine fish species of concern occur in the Powder and Tongue river basins (Montana Natural Heritage Program 2004; Wyoming Natural Diversity Database 2005) (Table 1). The larger rivers have more species of concern than cold water habitats or small prairie streams. Five species of concern occur primarily in at least one of the larger rivers (Yellowstone, Powder, and Tongue rivers): pallid sturgeon, shovelnose sturgeon, paddlefish, sturgeon chub, and blue sucker. Three species of concern occur in large prairie streams in addition to the larger rivers: goldeye, western silvery minnow, and sauger. Yellowstone cutthroat trout is the only species of concern that occurs in coldwater habitats. None of the nine species of concern has primary habitat in small prairie streams (Table 1).

Coalbed Natural Gas Development in the Powder River Basin

General process of CBNG extraction

Coalbed natural gas (CBNG) is formed in buried coal seams. Gas molecules are held in small cracks and pores of the coal seam by overlaying sediment layers and by hydrostatic pressure created by water in the coal seams. Gas is brought to the surface by drilling a well and pumping water out of the coal seam. When the hydrostatic pressure is reduced, the natural gas can migrate out of the spaces of the coal seam and move up the well to be piped away (Wheaton and Donato 2004a). The water that is pumped out of the coal seam is referred to as CBNG product water.

Potential for coalbed natural gas development exists in over 20 countries (Talkington 2002). Active exploration or production of coalbed natural gas is taking place in the United States, Canada, western Europe, Japan, Australia, and New Zealand (Talkington 2002; Johnson 2004). Currently, the United States is by far the largest producer of coalbed natural gas with six major basins actively developed, including the Black Warrior in Alabama, San Juan and Raton in Colorado and New Mexico, Piceance and Uinta in Utah, and the Powder River in Montana and Wyoming (Van Voast 2003).

Growth of CBNG development has been the greatest in the PRB. Coalbed natural gas development in the PRB is unique because of shallow coal beds that are inexpensive to drill and product-water quality that has been deemed suitable for inexpensive disposal (Wheaton and Donato 2004a). The rank, or quality, of coal is determined by the depth of burial overtime. Lower rank coals, such as those in the PRB, are buried at shallower depths and are generally less dense. Deeply buried, higher rank coal beds are the targets for coalbed natural gas development in other basins of the United States (Van Voast 2003). The difference in burial depths results in production of two distinct types of methane gas. Biogenic natural gas is biologically driven and produced by microbial action in shallow basins, such as the PRB. Thermogenic natural gas is produced by the changes coal undergoes from heat and pressure in deep, marine sedimentary basins, such as the other CBNG-producing basins in the United States (Van Voast 2003). These deeply buried coal seams are generally dense, whereas lower rank coal seams are less dense and have more interstitial spaces to hold water and gas molecules (Van Voast 2003). Low rank coal seams of the PRB have a low gas to water ratio and therefore, large quantities of CBNG product water are associated with the extraction of CBNG in the basin. Whereas great quantities of product water are produced in the PRB, its water quality is more similar to surface waters than the product water of the deeply buried coal beds, making it more eligible for surface water discharges or other uses (Rice et al. 2000; Van Voast 2003).

Product water disposal

Current management practices for the disposal of CBNG product water in the PRB include direct discharge to surface waters, discharge of treated water, impoundment, reinjection, irrigation, and other “beneficial uses.”

Direct discharge to surface waters.—Direct discharge to surface waters occurs when product water is delivered directly to a stream with a pipeline or when product water is released into an ephemeral channel that subsequently flows into an existing surface water. Permits for such point source discharges are subject to the National Pollution Discharge Elimination System (NPDES) permitting system and the regulations imposed by individual states. This permitting system generally considers water quality and quantity; however, limits established in permits may be less strict than necessary to protect biota and irrigation suitability (Confluence Consulting, Inc. 2004). In Montana, direct discharge to stream channels is not typically allowed on wells permitted after about 1999, but operations existing prior to this date were “grandfathered” and are still discharging directly into streams (ALL Consulting 2003). Proposals are being advanced to allow regulated direct discharges during certain flow periods on new well developments (BLM et al. 2003). The Wyoming Department of Environmental Quality (WYDEQ) had issued about 600 NPDES permits as of 2002 for CBNG product water discharges at nearly 3,000 different direct discharge points (Veil 2002). Multiple CBNG wells may be discharged from a single discharge point. Concerns surrounding direct discharge into stream channels include changes in flow regimes, the potential for bank erosion and degradation of stream beds, and changes in water quality that may be detrimental to native biota or irrigation suitability (ALL Consulting 2003). Direct discharge would be expected to have the greatest potential effect on fish assemblages of all disposal methods.

Discharge of treated water.—In some cases, product water is treated before it is discharged to surface waters. Product water subject to treatment is typically of poor water quality (>15,000 ppm TDS) and is placed in lined holding ponds during treatment. Treatment techniques include desalinization, UV sterilization, chemical treatment, reverse osmosis, and ion exchange processes (ALL Consulting 2003). Treatment technologies are limited to treating dissolved solids, organics, and conductive ions in concentrated product water (ALL Consulting 2003).

Impoundment.—Several types of impoundments are used depending on specific product water management needs. Impoundments may be in-channel or off-channel, and lined or unlined. In-channel impoundments use structures to create a barrier to downstream flow and capture water that would otherwise flow downstream. Potential discharges of product water down the stream channel occur during flooding or upon barrier failure (ALL Consulting 2003). Off-channel impoundments are typically placed and constructed to minimize the capture of surface water. Lined impoundments are used for holding product water until the next management action, such as irrigation or reinjection, is taken. In contrast, unlined impoundments are used as infiltration ponds that discharge product water to the subsurface. Whereas most water evaporates or infiltrates to deeper groundwater sources, an estimated 15-20% of water from unlined impoundments is likely to reach nearby stream channels by subsurface flow (ALL Consulting 2003). The most common use of impoundments is for disposal through evaporation or infiltration (ALL Consulting 2003).

As of June 2005, over 3,000 impoundments had been permitted in Wyoming (WOGCC 2005). The permitting requirements for impoundments vary from state to state, but are largely dependent on the quality of the impounded water and its eventual use (ALL Consulting 2003). Coalbed natural gas producers in Montana and Wyoming should collect hydrogeologic information at each site to determine the ability of the product water to affect the chemistry of shallow, unconfined groundwater, reach surface waters, or infiltrate into the subsurface (ALL Consulting 2003). Impoundment, particularly the use of infiltration ponds, may affect fish assemblages if product water enters surface waters.

Irrigation.—Some CBNG product water may be suitable for crop and rangeland irrigation by sprinkling or flooding. However, the potentially high salinity hazard of CBNG product water requires irrigators to carefully manage the dispersal of CBNG waters on their crops or rangeland (Keith et al. 2003). Surplus irrigation water will percolate through the soil and may seep into shallow aquifers or stream channels (Lindner-Lunsford et al. 1992). When irrigation rates are high, significant amounts of CBNG water can enter stream channels by surface and subsurface flow and mix with surface water (ALL Consulting 2003). As with infiltration ponds, irrigation may affect fish assemblages if product water enters stream channels.

Reinjection.—Underground injection wells currently are used in conventional oil, gas, and CBNG fields across the country. This water management strategy is dependent on the quality of the product water, the quality of the receiving water, the availability of a receiving geologic formation, and the storage capacity of the receiving geologic formation. The goal of reinjection is to dispose of poor-quality product water at depths that will not influence ground or surface waters used for anthropogenic purposes. Reinjection has proven to be environmentally safe and economical in many instances, but it is important that site-specific analyses be done. The current permitting system in Wyoming allows for area permits that apply to all reinjection wells in a given area. Differences in local hydrogeology and the design construction of some of the classes of reinjection wells may not provide adequate protection against possible groundwater contamination (ALL Consulting 2003). Reinjection of CBNG product water likely poses little threat to fish assemblages because the product water typically does not mix with surface waters. However, reinjection is not common in the PRB because it is not as economical as permitted surface discharges or impoundments.

Other "beneficial uses."—Product water may have beneficial uses for the CBNG and coal industries and farmers and ranchers (BLM et al. 2003). Product water is used for dust control, stock water, wildlife habitat, fisheries, and mining. Product water that is suitable for livestock and wildlife consumption has been used to create watering sites. These can be beneficial to ranchers by expanding cattle grazing into areas formerly limited by a lack of watering sites. Additionally, moving cattle to water sources away from streams may decrease the effects of grazing on stream banks and riparian vegetation, which may be good for fish.

Product water has been used to sustain privately owned fish ponds where water quality has been sufficient to support rainbow trout and smallmouth bass (ALL Consulting 2003). Wetlands have been created in some areas to provide wildlife habitat. However, any beneficial uses of CBNG product water for livestock, wildlife, and fisheries will be short-lived because CBNG development is not projected to last more than 20 years (ALL Consulting 2003). Beneficial uses of CBNG product water likely poses little threat to fish assemblages because there is little contact with surface waters, or in the case of fish ponds, product water quality is high.

Potential Effects on Fish in the Powder River Basin

Effects of CBNG development on fish in the PRB are generally unknown. Fishes native to the PRB have evolved life history strategies that allow them to survive in extreme conditions. However, water development that alters water quality or water quantity may nevertheless result in changes in the fish assemblage (Hubert 1993). Unfortunately, pre-development baseline data for small streams in the area are minimal, but many efforts are currently being made to gain a better understanding of the local fish assemblages. Whereas few studies have been conducted looking specifically at effects of CBNG development on fish in the PRB (Confluence Consulting, Inc. 2003; 2004), other studies conducted elsewhere addressed similar questions regarding changes in water quality and water quantity, and surface environment alterations such as road building. We reviewed the literature pertaining to these potential effects and considered the applicability of these studies to CBNG development in this section.

Water quality

All natural waters contain dissolved chemicals introduced from the atmosphere, soil, rocks, or by human activities. The geologic setting plays an important role in creating the chemical signature of water, which may be used to infer its source (Van Voast 2003). Dissolved chemicals found in CBNG product water can be highly variable among wells and differ greatly from those in surface waters in the PRB because of their origin within coal seam aquifers (Clearwater et al. 2002; Van Voast 2003). Whereas the chemistry of CBNG product water is highly variable, generalizations exist. Water from coal seam aquifers is higher than surface waters in dissolved Na^+ and HCO_3^- whereas surface waters in the PRB generally are higher in dissolved Ca^{2+}, Mg^{2+}, chloride (Cl^-), and SO_4^{2-} (Clearwater et al. 2002; Figure 1). Conductivity, TDS, and alkalinity of CBNG product water tends to increase from wells located in the southeast portion of the PRB to wells located in the northern and western areas of the PRB (Clearwater et al. 2002). CBNG product water can be highly variable even among wells located at similar depths in the same geological formation and less than 32 km apart (Clearwater et al. 2002). CBNG product water was significantly higher in pH, electrical conductivity, TDS, alkalinity, Na^+, Ca^{2+}, Mg^{2+}, and K^+ in wells located in the Little Powder River drainage basin than wells in Cheyenne River drainage basin (McBeth et al. 2003).

The chemical properties of CBNG product water at or near the point of discharge are monitored and generally well known. However, as product water mixes with surface water and achieves equilibrium with the atmosphere, product water chemistry changes (Sessoms et al. 2002). Several efforts have been made to understand and monitor the chemistry of the product water, and more recently to understand the changes CBNG water undergoes when exposed to environmental factors (Rice et al. 2000; Sessoms et al. 2002; McBeth et al. 2003; Patz et al. 2004). Monitoring CBNG product water only at well heads may not be sufficient to detect actual effects to downstream water (Patz et al. 2004).

Surface waters in the drainage basins of the PRB also vary in water quality. The ranks of conductivity in surface water basins of the PRB from highest to lowest is the Belle Fourche River, the Little Powder River, the Powder River, Piney Creek, and the Tongue River (Figure 2). Because both surface waters and product water in the PRB are variable, surface waters can be lower or higher in conductivity than product water (Figure 2). Therefore, in some locations product water may tend to “salinize” surface waters, and in other locations, product water may tend to “dilute” surface waters. However, both dilution and salinization have potential to affect native aquatic biota (Clearwater et al. 2002), particularly if ion composition differs from that found in the surface waters where the biota evolved.

Salinity.—The salinity of water generally refers to the concentration of mineral salts dissolved in water. Salinity may be measured by weight (total dissolved solids) or electrical conductivity (APHA 1998). Total dissolved solids are a quantitative measure of the residual minerals dissolved in water that remain after evaporation of a solution, typically expressed in milligrams per liter (mg/L) or in parts per million (ppm), which are equivalent. Conductivity is a measure of the ability of an aqueous solution to carry an electric current. The presence of ions, their total concentration, mobility, and valence as well as water temperature determine the conductivity of water (APHA 1998). Sodium adsorption ratio (SAR) is a measurement of the relative proportion of sodium to other cations and is typically used in agriculture to determine the suitability of water for irrigation (Jain 2005). Whereas SAR is an important water quality issue for irrigators, it has limited inference to aquatic environments.

Salinity can be a dominant factor in structuring stream fish assemblages (Higgins and Wilde 2005). Increases in salinity as intermittent pools lost water volume by evaporation were related to the likelihood of persistence of fish species in Texas streams (Ostrand and Wilde 2001; Ostrand and Wilde 2004; Higgins and Wilde 2005). Whereas cyprinids were absent from pools where salinity exceeded 21‰, cyprinodontids persisted in pools with salinities ranging to 44‰ (Ostrand and Wilde 2004). Biodiversity typically decreases in salinized rivers and streams as low salinity tolerant taxa are extirpated and only high salinity tolerant taxa can persist (Williams 2001). About 60% of low and moderate salinity tolerant fishes present before a period of drought in the 1950s were apparently extirpated in the Red River drainage of Oklahoma and Texas from the 1950s to the 1990s, compared to the apparent extirpation of only 14% of high salinity tolerant species (Higgins and Wilde 2005).

Oilfield brine discharges can increase salinity of nearby streams and have negative effects on aquatic biota. Oilfield brines raised instream chloride levels from an average of less than 10 ppm to often exceeding 1,000 ppm in Green River, Kentucky, and fish species richness averaged 38 species in stream sections receiving brines compared to an average of 56 species in stream sections upstream of brine sources (Charles 1964). Petroleum well brine discharges in Petronella Creek, Texas, increased conductivity from 974 µmhos above discharge sites to as high as 29,551 µmhos below discharge sites. Fish species richness was reduced from about 20 species above brine discharge sites to 0 to 4 species below discharge sites (Shipley 1991).

Salt Creek, a tributary to the Powder River in Wyoming, receives oil field brines (Boelter et al. 1992). Conductivity, alkalinity, pH, and concentrations of Na^+, K^+, Cl^-, HCO_3^-, and CO_3^{2-} increased in the oil fields and generally decreased downstream. Conductivity in Salt Creek above the oil fields ranged from 4,170 to 4,840 µmhos ($N = 5$), whereas it ranged from 6,000 to 6,740 µmhos ($N = 5$) below the oil fields. Conductivity in the Powder River above the confluence of Salt Creek ranged from 828 to 2,500 µmhos ($N = 3$), whereas it ranged from 1,688 to 5,930 µmhos ($N = 4$) below Salt Creek. Survival and reproduction of *Ceriodaphnia dubia* was significantly reduced in ambient water samples collected downstream of the oil fields, and toxicity increased as ion and element concentrations increased during periods of low stream discharge. Alkalinity, Cl^-, Na^+, K^+, and pH explained from 81% to 94% of the variance in *C. dubia* survival. In contrast to *C. dubia*, the survival of fathead minnows was not affected by the test conditions. However, during a period of low stream discharge and increased ion concentrations, growth of fathead minnows was significantly reduced in water samples collected below oil fields (and from the Powder River upstream of Salt Creek), relative to growth of fathead minnows in water from Salt Creek upstream of the oil fields (Boelter et al. 1992).

Metals and trace elements.—Levels of several metals and trace elements in water, sediments, aquatic vegetation, aquatic invertebrates, salamanders, and fish from wetlands and containment ponds receiving CBNG product water exceeded WYDEQ standards, or other biologically relevant levels (Ramirez 2005). One CBNG product water discharge exceeded the WYDEQ chronic criterion for copper (Cu) and several CBNG product water discharges exceeded the WYDEQ chronic criterion for iron (Fe). Concentrations of arsenic (As), cadmium (Cd), nickel (Ni), and zinc (Zn) in sediment samples from a wetland receiving CBNG product water were high enough for potential adverse effects on sediment-dwelling organisms. Boron (B), cadmium, and chromium (Cr) levels in some aquatic vegetation samples and cadmium levels in some aquatic invertebrate samples exceeded levels of concern for wildlife dietary thresholds. Chromium levels in tiger salamanders (Ambystoma tigrinum) and fathead minnows were indicative of chromium contamination. Selenium (Se) levels in CBNG product water and impoundments exceeded a threshold for bioaccumulation in sensitive species of fish and aquatic birds. However, because no data exist for this area prior to the development of CBNG, it is not known if these levels are natural or related to CBNG development (Ramirez 2005).

pH.—Fish tolerance of pH levels depends on factors such as dissolved oxygen, temperature, prior acclimatization, and ion composition. Direct lethal effects of pH to fish are not observed within a range of 5.0 to 9.5 and productivity is highest within a range of 6.5 to 8.2 (Anonymous 1955). Several fish species were able to tolerate extensive and rapid changes in pH from 7.2 to 9.6 and 8.1 to 6.0 (Weibe et al. 1934). The mean pH of product water from 47 wellheads in the PRB was 7.3 and ranged from 6.8 to 7.7 (Rice et al. 2000), whereas pH of surface waters in the PRB ranges from 7.7 to 8.8 (Linder-Lunsford et al. 1992; Clearwater et al. 2002). These pH levels of CBNG product water (Rice et al. 2000) are within the optimal range for fish productivity, however pH of product water discharged to ephemeral stream channels increased from 7.1 to 8.8 after being exposed to the atmosphere and reacting with soils (McBeth et al. 2003; Patz et al. 2004). These spatial and temporal changes in water chemistry make it difficult to predict the pH fluctuations of CBNG product water and the potential effects on fish assemblages.

Dissolved oxygen.—Dissolved oxygen concentration (DO), the amount of oxygen that is dissolved in water, is one of the most important parameters of water quality to fish. Dissolved oxygen levels below 5.0 mg/L can stress aquatic life and prolonged periods of low DO can result in fish kills (Ji 2005). The amount of DO in perennial surface waters of the PRB ranged temporally from 5.4 to 14.7 mg/L (Linder-Lunsford et al. 1992). Isolated pools in intermittent streams also experience large daily fluctuations in dissolved oxygen levels (Tramer 1977; Ostrand and Wilde 2001). Fish tolerance to low dissolved oxygen concentrations decreases with increased pH (Powers 1922; Weibe et al. 1934; Townsend and Cheyene 1944). Low DO levels (2.8 to 3.2 ppm) in headwater streams were associated with oil field discharge (Whiteside and McNatt 1972). CBNG product waters are typically low in DO (ALL Consulting 2003), but no information was found regarding specific DO levels of CBNG product waters in the PRB. However, DO concentrations in CBNG product water likely vary depending on the aquifer source and the level of aerobic or anaerobic activity at the extraction point (ALL Consulting 2003). Additionally, DO concentrations will increase above ground as a result of surface agitation (ALL Consulting 2003).

Turbidity.—Turbidity is a measure of water clarity and light transmission. Suspended matter such as silt, clay, and fine organic and inorganic matter create the levels of turbidity found in water. Turbidity is considered an adverse water quality characteristic affecting about 34% of the streams in the United States (Judy et al. 1988). However, most Great Plains streams are characteristically turbid and support native fish assemblages that have evolved under such conditions. Surface waters of the PRB have stochastic flow regimes resulting in fluctuating turbidity levels. The Powder River was named for its milky appearance. Turbidity of the Powder River ranges from 20 to 8,000 JCU with a median of 475 JCU (Clearwater et al. 2002). No information is available on the turbidity levels of CBNG product water, but the authors have noted that product water can be less or more turbid than nearby surface waters.

Non-native sight feeding fish may have a competitive advantage over native fish if CBNG product water decreases the turbidity of surface waters in the PRB. Many of the native fish found in the Powder River are non-sight feeders. Reduced turbidity in Midwestern prairie rivers has been hypothesized as contributing to the replacement of non-sight feeders with sight-feeding species. Turbid water gave non-sight feeding gizzard shad (*Dorosoma cepedianum*) competitive advantage over sight feeding bluegill (*Lepomis macrochirus*) (O'Brien 1977). Decreased turbidity may also increase predation on native species where introduced sight-feeding predators have become established. For example, turbidity may visually isolate creek chubs from predators such as brook trout (Gradall and Swenson 1982). Conversely, increased turbidity of surface waters caused by CBNG product water may affect fish assemblages by favoring those species more tolerant of turbid conditions. Elevated turbidity had less effect on prey consumption by species adapted to turbid environments (flathead chub) than on fish adapted to less turbid environments (sand shiner) (Bonner and Wilde 2002). Increased turbidity in areas of the PRB with relatively low turbidity may allow native species adapted to turbidity to expand their ranges or relative abundances in these areas.

Temperature.—Temperature affects virtually all activities of fishes. Most fish are ectotherms, with low metabolic rates and no insulation or countercurrent lamellar blood-water flow; therefore body temperature of most fish is a direct function of water temperature (Beitinger et al. 2000). The uppermost temperature tolerances of fish species are above the ambient temperatures of their natural habitats (Mundahl 1990). Major fish families of the PRB (i.e., Cyprinidae, Catostomidae, Centrarchidae and Ictaluridae) all have critical thermal maxima greater than 30 ºC (Beitinger et al. 2000). Temperatures of CBNG product water and surface waters do not exceed this threshold; the mean temperature of product water from 47 wellheads in the PRB was 19.6 ºC and ranged from 13.8 to 28.7 ºC (Rice et al. 2000) whereas surface waters ranged from 0.0 to 30.0 ºC (Linder-Lunsford et al. 1992).

Surface waters of the PRB normally freeze in winter, but continual addition of CBNG product water to surface waters has resulted in some isolated areas that do not freeze (B. Stewart, Wyoming Game and Fish Department, personal communication 2005). Moreover, seasonal change in water temperature is an important environmental cue for the movement and spawning behavior some fish species (Gale 1986; Bjornn and Reiser 1991). Continuous input of constant-temperature CBNG product water may disrupt natural environmental cues and result in temporal changes in fish behavior and reproduction (Clearwater et al. 2002).

Potential effects of CBNG product water on fish.—Demonstrated effects of CBNG product water on fish are ambiguous. Fathead minnows and rough shiners exposed to CBNG product water from the Black Warrior basin, Alabama, had no significant mortality at Cl^- concentrations as high as 2,160 mg/L (Mount et al. 1993). Acute toxicity of 7 water samples from CBNG wellheads and 23 water samples from streams receiving CBNG product water in the PRB was tested on fathead minnows (Forbes 2003). None of the CBNG well head samples were toxic to fathead minnows, but two stream-water samples caused significant acute mortality of fathead minnows. However, these results are equivocal with respect to CBNG product water because the proximity of CBNG product water discharge relative to the sample location was not known. Moreover, the chemical constituent that caused the observed mortality could not be identified because constituent concentrations were either in concentrations below published lethal levels or were below levels in other samples from the study that did not cause mortality (Forbes 2003).

Newly hatched pallid sturgeon and fathead minnows were exposed to 518, 864, 1,440 and 4,000 mg/L $NaHCO_3$ to determine acute toxicity under two separate test conditions (Skaar et al.

2004). The two test conditions were reconstituted "Tongue River" and "Powder River" water, which were based on average water quality conditions in the two rivers. The "Powder River" water had higher Cl^-, SO_4^{2-}, Ca^{2+}, Mg^{2+}, Na^+, potassium (K^+), and HCO_3^- levels than the "Tongue River" water. Ninety-six h LC50s of pallid sturgeon were 1,158 mg/L $NaHCO_3$ in Powder River water, and 1,828 mg/L $NaHCO_3$ in Tongue River water. The 96-h LC50 of fathead minnows was 1,643 mg/L $NaHCO_3$ in Powder River water. Mortality was insufficient (23% at the 4,000 mg/L $NaHCO_3$) to calculate a LC50 for fathead minnows in Tongue River water (Skaar et al. 2004).

Of ten salts tested in the laboratory for acute toxicity to fathead minnows, the four salts with the lowest 96-h LC50s values were $KHCO_3$ (<510 mg/L), K_2SO_4 (680 mg/L), $NaHCO_3$ (<850 mg/L), and KCl (880 mg/L) (Mount et al. 1997). The most toxic (96-h fathead minnow LC50) two-salt combinations were $K_2SO_4/KHCO_3$ (720 mg/L), $NaHCO_3/KHCO_3$ (740 mg/L), KCl/ K_2SO_4 (760 mg/L), and KCl/$KHCO_3$ (770 mg/L). Laboratory-derived logistic regression models for toxicity of major ions to fathead minnows predicted 50% mortality at the following ion concentrations: $K^+ \approx 500$ mg/L, $Mg^{2+} \approx 1,800$ mg/L, $HCO_3^- \approx 2,000$ mg/L, and $Cl^- \approx 4,500$ mg/L. However, SO_4^{2-} was not predicted to cause 50 % mortality at concentrations up to 5,000 mg/L, and Na^+ and Ca^{2+} concentrations were not significant variables in fathead minnow mortality models (Mount et al. 1997).

Short-term laboratory tests do not capture potential longer term effects on growth, reproduction, and survival of fish because culturally derived salts in concentrations below known lethal concentrations affect growth and survival in chronic exposures. Fathead minnow eggs were hatched at 500, 800, 1,100, and 1,400 mg/L $NaHCO_3$ to assess the chronic toxicity of $NaHCO_3$, the major salt in CBNG product water from the PRB (Skaar et al. 2004). The estimated hatch rate was 43.9% at 1,400 mg/L $NaHCO_3$, and 62.5% in the control tank. Post hatch survival rate of the 96-h control was 94.3% whereas the survival rate was only 8.1% at $NaHCO_3$ concentrations of 1,400 mg/L. At 37 d, survival rate was 89% in the control and only 2.4% at 1,400 mg/L $NaHCO_3$. Excessive mortality by day 37 in tests at 800, 1,100, and 1,400 mg/L $NaHCO_3$ prohibited calculation of a 60-d LC50 (Skaar et al. 2004). Gill lesions, kidney damage, and degeneration of ovarian tissue in fathead minnows increased with $NaHCO_3$

concentrations or number of days of exposure (Skaar et al. 2005). White suckers were more tolerant to elevated levels of $NaHCO_3$ than fathead minnows and pallid sturgeon (Skaar et al. 2005). The 96-h LC50 of newly hatched fry was 5,121 mg/L $NaHCO_3$ in Tongue River water and 5,421 mg/L $NaHCO_3$ in Powder River water. An LC50 could not be calculated for older fry; they appeared to be more tolerant than newly hatched fry (Skaar et al. 2005).

Laboratory tests provide some insight, but cannot address all of the potential effects of CBNG waters on fish because they do not characterize actual field conditions. Surface water chemistry fluctuates in the field, and CBNG product water changes as it reacts with soils, the atmosphere (Patz et al. 2004), and surface waters. Moreover, CBNG product water in the PRB is spatially variable (Clearwater et al. 2002). Laboratory tests typically use the fathead minnow, which is relatively tolerant of salts. Fathead minnow eggs and larvae withstood concentrations of salts four times greater than concentrations lethal to walleye and northern pike eggs and larvae (Peterka 1972). Fathead minnows can survive NaCl concentrations of up to 8,700 mg/L (Kochsiek and Tubb 1967) and were more tolerant than *Daphnia magna* of most salt combinations (Mount et al. 1997). Use of a tolerant species such as fathead minnow would underestimate effects on more sensitive species. Information on toxicity of CBNG product water on many fish species in the PRB is generally lacking, presenting a substantial gap in predicting effects of saline discharges on these ecosystems (Confluence Consulting, Inc. 2003). Survival rates to hatching of white suckers, walleye, northern pike, yellow perch, and common carp were significantly lower in sodium sulfate type waters greater than 2,400 mg/L TDS than in fresh water of 200 mg/L (Koel and Peterka 1995). Oxygen consumption rates and overall metabolic rates increased significantly in southern redbelly dace (*Phoxinus erythrogaster*) and northern studfish (*Fundulus catenatus*) as salinity was increased from 0‰ to 4‰ to 10‰ (Toepfer and Barton 1992). Sublethal concentrations of dissolved solids reduced growth in chinook salmon (*Oncorhynchus tshawytscha*) and striped bass (*Morone saxatilis*) (Saiki et al. 1992). Total dissolved solids decreased growth and survival of Lahontan cutthroat trout (*O. clarkii henshawii*) (Dickerson and Vineyard 1999).

Few field studies have examined the effects of CBNG product water on fish. Water chemistry and fish assemblages in Squirrel Creek, a Tongue River tributary, downstream of

CBNG development areas were markedly different than those found upstream of the CBNG development area (Confluence Consulting, Inc. 2003). Levels of HCO_3^- (541 mg/L), total alkalinity as $CaCO_3$ (443 mg/L), SO_4^{2-} (420 mg/L), Mg^{2+} (124 mg/L), Na^+ (76 mg/L), and conductivity (1,440 µmhos) in upper Squirrel Creek were lower than levels of HCO_3^- (892 mg/L), total alkalinity as $CaCO_3$ (731 mg/L), SO_4^{-2} (3,450 mg/L), Mg^{2+} (621 mg/L), Na^+ (936 mg/L), and conductivity (5,790 µmhos) in lower Squirrel Creek. The levels of these parameters in lower Squirrel Creek in 2003 were higher than the maximum levels measured in the 1970s. Moreover, levels in lower Squirrel Creek in 2003 also exceeded the 90th percentiles of measurements from a reference data set generated by summarizing historical measurements in an Environmental Protection Agency database for 26 comparable streams in the Tongue and Powder drainage basins (Confluence Consulting, Inc. 2003). Fish assemblages in upper Squirrel Creek were healthy, of high density, and diverse (five native species), but no fish were captured in lower Squirrel Creek. No direct discharges of CBNG product water are permitted on Squirrel Creek, suggesting the source of salt loading may be seepage from holding ponds in the drainage or geologic formations (Confluence Consulting, Inc. 2003). Some measurements of HCO_3^- (1,570 mg/L), and Cl^- (19.6 to 28.1 mg/L) in Spotted Horse Creek, a Powder River tributary receiving CBNG product water, exceeded the maximum levels from the reference data set, and SO_4^{2-} (2,520 to 3,810 mg/L), Ca^{2+} (175 to 225 mg/L), Mg^{2+} (249 to 338 mg/L), Na^+ (76 mg/L), K^+ (19.8 to 23.3 mg/L), and conductivity (4,560 to 6,460 µmhos) exceeded the 90th percentiles of the reference data set (Confluence Consulting, Inc. 2004).

Varying levels of water quality alterations of Little Hurricane Creek (O'Neil et al. 1991) and the Big Sandy Creek drainage (Shepard et al. 1993) in the Black Warrior Basin of Alabama occurred with the direct discharge of CBNG product water. During low flows, Cl^-, Na^+, HCO_3^-, iron (Fe), and some metal concentrations below discharge points were elevated 5 to 15 fold above pre-discharge levels. However, HCO_3^- levels in product water discharged into the Big Sandy Creek drainage were lower than those more typical of the Black Warrior Basin (O'Neil et al. 1991; Shepard et al. 1993). Average annual flow was typically sufficient to dilute the CBNG product water, although discharge of Little Hurricane Creek dropped to less than 0.03 m^3/s for four days of the study, during which instream Cl^- concentrations exceeded the threshold of 565 mg/L determined to be safe for fish. However, no significant decline in fish species diversity or total fish biomass occurred after discharge of CBNG product water began (O'Neil et al. 1989; O'Neil et al.1991; Shepard et al. 1993). Fish species differed in their response to CBNG discharge in the drainage. Whereas the abundance of Gulf darters decreased in the presence of product water, reproduction of the rough shiner was significantly greater downstream of discharge (O'Neil et al. 1991). These subtle patterns of fish species variation observed suggested that the aquatic system was changing and that long periods of CBNG product water discharge may result in changes in assemblage composition (O'Neil et al. 1991). Fish populations were reflective of water-quality conditions and should be used to assess the biological integrity of streams (O'Neil 1993).

The major ion composition of product water varies among geologic basins limiting the inferences that can be made between basins (Mount et al. 1993). For example, Cl^- was the primary concern in CBNG product water in the Black Warrior Basin, whereas HCO_3^- and Na^+ are likely more important in the PRB. Additionally, naturally intermittent streams may not provide the same opportunity for dilution in the arid environment of the PRB as found in the Black Warrior Basin. Chemistry of CBNG product water and surface water also varies within the PRB (Clearwater et al. 2002; McBeth et al. 2003).

Discharge limitations on TDS and conductivity are implemented by the Montana and Wyoming departments of environmental quality, but because ions, salts, and salt combinations vary widely in their toxic effects on aquatic life (Mount et al. 1997) general parameters such as TDS and conductivity may not be sufficient to protect aquatic life. Relative toxicity of different ions varies (Mount et al. 1997); K^+ is the most toxic to *C. dubia, Daphnia magna,* and fathead minnows, followed by HCO_3^-, Mg^{2+}, Cl^-, and SO_4^{2-}. Tolerance levels are typically determined through tests of single ions, but the presence of other constituents complicates toxicity determinations (Mount et al. 1993). Mortality of sheepshead minnow (*Cyprinodon variegatus*) in oil well brines was reached at salinity levels within their normal tolerance range, indicating a synergistic effect of other toxic constituents (Andreasen and Spears 1983).

Water quantity

The naturally stochastic and unaltered flow regime of the Powder River makes it unique and relatively pristine (Hubert 1993). Fishes endemic to the PRB have evolved life history strategies that allow them to survive in extreme conditions. However, water development that alters flow regimes or water quality may result in changes in the fish assemblage (Hubert 1993). Proposed reservoirs on the mainstem of the Powder River would have threatened the continued existence of the sturgeon chub, goldeye, and shovelnose sturgeon (Wyoming Game and Fish Department 1983). Alterations to the natural flow regime should be considered potentially harmful to the native fish fauna of the PRB (Wyoming Game and Fish Department 1983; Hubert 1993).

Increased discharge.—During CBNG production, wells pump water to the surface to lower the hydrostatic pressure near the top of the coal seam. Water levels are then maintained at this elevation during production (Wheaton and Donato 2004b). The large amount of groundwater pumped to the surface during CBNG development increases surface water quantity and may decrease groundwater sources. As of August 2003, the 11,809 producing CBNG wells in the Wyoming portion of the PRB collectively pumped about 227 million L of product water per day, an amount equivalent to a stream of 2.6 m^3/s (WOGCC 2005). The amount of water produced varies among wells and generally decreases over the lifetime of the well. However, total discharge from all wells will increase as new wells are completed (Wheaton and Donato 2004b). Variability in amounts of water produced and rapidly evolving water disposal methods complicate quantifying product water in a manner useful for assessing the effects to aquatic biota.

Coalbed natural gas product water may change natural patterns of stream discharge in the PRB, particularly in streams where intermittent or ephemeral surface water discharges are typical. Coalbed natural gas wells transport product water to this arid surface environment throughout the year. The environmental cues associated with seasonal cycles in water quantity may be dampened by constant inflows of CBNG product potentially affecting spawning and migratory cues of resident aquatic biota (Clearwater et al. 2002). Fishes of the PRB are adapted to a naturally stochastic flow regime and stabilized discharge could allow for invasion of nonnatives. Also, constant discharge of water in streams may alter the habitat found in slow moving waters or standing pools. Intermittent streams provided an ideal nursery environment for white suckers and creek chubs because they warmed earlier than perennial streams allowing for a longer growing season for age-0 fish, and the lack of discharge excluded large predators (Williams and Coad 1979).

Local geology, climate, well densities, water productions rates, water disposal methods, and groundwater resources influence the amount of deviation from normal historic flow regimes (Greystone Environmental Consultants, Inc. and ALL Consulting 2003). Obvious increases in surface water volumes attributable to direct discharge have occurred in some areas such as Burger Draw, Beaver Creek, and Pumpkin Creek, Wyoming. These creeks were ephemeral or intermittent tributaries of the Powder River that have been perennialized by continuous addition of CBNG product water and could potentially alter the flow regime of the Powder River itself. Additionally, direct discharges into the mainstem Powder and Tongue rivers are permitted. The effects of the addition of product water on the annual hydrograph and aquatic habitats have not been quantified. Currently, USGS is conducting a study to assess the habitat and geomorphology of the Powder River at various discharge levels. This study may provide useful information about changes in habitats caused by the input of product water to the Powder River.

Decreased discharge.—Pumping of coal seam aquifers may lead to the reduction of water inputs from springs and hyphorheic flow that help maintain pools in some parts of the PRB (Wheaton and Metesh 2002). The long term potential for aquifer drawdown by CBNG production in southeastern Montana has been predicted by a model, USGS Modflow, which predicts the relative declines in potentiometric head in CBNG aquifers that may result from CBNG development (Wheaton and Metesh 2002). Maximum drawdown was predicted to range from 67 to 167 m within areas of active CBNG development. Drawdown of more than 3 m within the coal aquifers can be expected to reach 1.6 to 3.2 km outside the producing fields during the early years of production and distances of 8 to 16 km, or more, during long-term production. Hydrology differs throughout the PRB and the USGS Modflow model was created using site-specific data from the Anderson, Canyon, and Wall coals, which are all undergoing CBNG development. The model recognizes that drawdown may not affect some waterways, including the Tongue River and Squirrel Creek, but it also claims to probably underestimate drawdown outside the field, overestimate water production, and underestimate the time to recover (Wheaton and Metesh 2002). Discharge from springs and the water available at wells supplying water for livestock, wildlife, and domestic uses may be diminished or eliminated within the areas of drawdown. These springs often create important refugia for fish during low discharge. The decrease in discharge will be proportional to the decrease in hydrostatic pressure in the aquifer at the well or spring. Lowering the water level may also dry up intermittent pools of streams because they are directly connected to groundwater (Dodds et al. 2004).

Great Plains streams exist in a flux between flooding and drying (Dodds et al. 2004). Therefore, many fishes of the PRB are adapted to periods of low water availability, particularly those that inhabit small prairie streams (Table 1). Isolated pools in intermittent streams provide important refugia for fish during such extreme conditions (Zale et al. 1989; Bramblett and Fausch 1991; Fausch and Bramblett 1991; Bramblett and Zale 2000; Labbe and Fausch 2000; Dodds et al. 2004; Bramblett et al. 2005). Heat death of orangethroat darters was observed in small intermittent pools of Brier Creek, Oklahoma, but not in larger pools (Matthews et al. 1982). Brassy minnows were more likely to survive in large pools than smaller pools (Scheurer et al. 2003). Land use alterations that may reduce the size and frequency of permanent pools may deleteriously affect fish assemblages in intermittent streams (Zale et al. 1989).

Surface environment alterations

A set of wells in a grid pattern called a pod is created to efficiently produce CBNG (Wheaton and Donato 2004a). Pods allow the hydrostatic pressure to be reduced over a large area of the coalbed, thereby increasing the rate of gas production. Pods typically cover 13 to 39 km^2 and contain about four wells per 2.6 km^2 in each coal seam. Well densities vary because in some areas up to five coal seams of different depths are targeted. In these situations, separate wells are drilled to each coal seam raising densities to as many as twenty wells per section (Wheaton and Donato 2004a).

Development of a pod involves several types of surface modifications (Wheaton and Donato 2004a). Typically, a central road is built or a pre-existing road is used as the center divider of a pod. Secondary roads, buried gas and water pipelines, and buried electric cables are installed in a branching formation to each CBNG well site. Low-pressure compression stations are built at the center of each pod to receive CBNG from each well. Additionally, product water is piped to treatment facilities, discharge points, or holding impoundments. About 1.3 to 1.7 ha are disturbed by the installation of each CBNG well and road densities may reach from 5 to 19 km per km^2 (BLM et al. 2003).

Sedimentation.—The construction of roads, well pads, compressor stations, and pipelines associated with CBNG development has the potential to increase sedimentation of local streams. The effects of sedimentation on fish have been intensively studied in relation to road building, urban development, logging, and dam construction. Sediments can affect salmonid fishes by interfering with the development of eggs and larvae, modifying natural movements and migrations, and reducing the abundance of food organisms available to fish (Newcombe and MacDonald 1991). Additionally, sedimentation reduces the amount of habitat diversity and in turn the diversity of fish than can be supported in a stream (Berkman and Rabeni 1987). Great Plains streams are naturally high in fine substrates, but the scarcity of coarse substrates may make them particularly important (Bramblett et al. 2005). Whereas some streams of the PRB have naturally high sediment loads, others have a rockier substrate than the Powder River and provide important spawning habitat for migratory fish (Smith and Hubert 1989). The elimination of rare exposed coarse substrates could cause changes in the fish assemblages by reducing reproductive opportunities for litho-obligate species such as goldeye (*Hiodon alosoides*), sturgeon chub (*Macrhybopsis gelida*), longnose dace (*Rhinichthys cataractae*), and sand shiner (*Notropis stramineus*).

Culverts.—Increased road construction associated with CBNG development may lead to increased stream crossings. Poorly designed and installed stream crossings may create artificial barriers to fish (Gibson et al. 2005). Culverts create more barriers to fish passage than other forms of crossings. However, they are relatively inexpensive and are installed more frequently than bridges (Warren and Pardew 1998). Movement of stream fishes is important for gene flow (Bell and Richkind 1981) and recolonization of dewatered sites (Labbe and Fausch 2000). Fragmentation of fish assemblages in Great Plains streams can lead to decreased diversity

(Winston et al. 1991). Culvert crossings reduced or blocked movement of centrarchids, cyprinids, cyprinodontids, and percids in small streams in Arkansas (Warren and Pardew 1998). However, preliminary data from tributaries of the Yellowstone River suggest that properly installed culverts with little or no outlet drop allow passage of small prairie fish at most discharge levels (L. Rosenthal, Montana State University, personal communication 2005).

Impoundments.—Whereas in-channel impoundments built to retain CBNG product water are no longer commonly permitted, existing impoundments may alter flow regimes and block migration of fish. Impoundment of prairie streams has created barriers to fish movement and led to the extirpation of several minnow species (Eberle et al. 1986; Winston et al. 1991). Failure of impoundments may lead to an influx of CBNG product water or sediments into streams.

Impoundments are often a source of introduced fish species. In Wyoming, impoundment of the Laramie River at Grayrocks Reservoir served as a source of introduced piscivorous fishes that had a substantial effect on native fish assemblages (Quist et al. 2005). Impoundments for CBNG waters may be stocked with non-native fish such as western mosquitofish (*Gambusia affinis*) for mosquito control because of concerns regarding West Nile virus. Resource managers should consider using native fish species for mosquito control because flooding events may allow fish from impoundments to migrate into surface waters where they will interact with native fishes (Harrel et al. 1967). Western mosquitofish may have negative effects on native fish assemblages. They reduced average survival of juvenile least chub (*Iotichthys phlegethontis*) by one-third in experiments in a desert spring ecosystem (Mills et al. 2004). Moreover, native fathead minnows are probably an ideal fish species for mosquito control because they are ubiquitous, tolerant of poor water quality, and easy to culture.

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Table 1. Fishes of the Tongue and Powder rivers, Montana and Wyoming.

Family Common name, *Genus species*	Species of concern[a]	Origin[b]	Primary habitats[c]					
			Yellowstone River	Powder River	Tongue River	Large prairie streams	Small prairie streams	Cold water habitats
Acipenseridae								
pallid sturgeon, *Scaphirhynchus albus*	MT	N	X					
shovelnose sturgeon, *Scaphirhynchus platorynchus*	WY	N	X	X				
Polyodontidae								
paddlefish, *Polyodon spathula*	MT	N	X					
Hiodontidae								
goldeye, *Hiodon alosoides*	WY	N	X	X	X	X		
Cyprinidae								
goldfish, *Carassius auratus*		I			X			
lake chub, *Couesius plumbeus*		N			X	X	X	
common carp, *Cyprinus carpio*		I	X	X	X	X	X	
western silvery minnow, *Hybognathus argyritis*	WY	N	X	X	X	X		
brassy minnow, *Hybognathus hankinsoni*		N				X	X	
plains minnow, *Hybognathus placitus*		N		X	X	X	X	
sturgeon chub, *Macrhybopsis gelida*	MT, WY	N	X	X				
golden shiner, *Notemigonus crysoleucas*		I			X			
emerald shiner, *Notropis atherinoides*		N	X		X	X		
sand shiner, *Notropis stramineus*		N		X	X	X	X	
fathead minnow, *Pimephales promelas*		N		X	X	X	X	
flathead chub, *Platygobio gracilis*		N	X	X	X	X		
longnose dace, *Rhinichthys cataractae*		N	X	X	X	X	X	X
creek chub, *Semotilus atromaculatus*		N			X	X	X	
Catostomidae								
river carpsucker, *Carpoides carpio*		N	X	X	X	X		
longnose sucker, *Catostomus catostomus*		N	X		X			X
white sucker, *Catostomus commersonii*		N	X		X	X	X	
mountain sucker, *Catostomus platyrhynchus*		N	X		X	X		X
blue sucker, *Cycleptus elongatus*	MT	N	X					
smallmouth buffalo, *Ictiobus bubalus*		N	X					
bigmouth buffalo, *Ictiobus cyprinellus*		N	X					

Table 1. Continued.

Family Common name, *Genus species*	Species of concern[a]	Origin[b]	Primary habitats[c]: Yellowstone River	Powder River	Tongue River	Large prairie streams	Small prairie streams	Cold water habitats
Catostomidae								
shorthead redhorse, *Moxostoma macrolepidotum*		N	X	X	X	X		
Ictaluridae								
black bullhead, *Ameiurus melas*		I			X	X	X	
yellow bullhead, *Ameiurus natalis*		I			X			
channel catfish, *Ictalurus punctatus*		N	X	X	X	X		
stonecat, *Noturus flavus*		N	X	X	X	X		
Esocidae								
northern pike, *Esox lucius*		I			X	X		
Cyprinodontidae								
plains killifish, *Fundulus zebrinus*		I		X		X	X	
Gasterosteidae								
brook stickleback[d], *Culaea inconstans*		N					X	
Salmonidae								
golden trout, *Oncorhynchus aguabonita*		I						X
Yellowstone cutthroat trout, *Oncorhynchus clarkii bouvieri*		N						X
rainbow trout, *Oncorhynchus mykiss*		I						X
mountain whitefish, *Prosopium williamsoni*		N						X
brown trout, *Salmo trutta*		I						X
brook trout, *Salvelinus fontinalis*		I						X
lake trout, *Salvelinus namaycush*		I						X
Gadidae								
burbot, *Lota lota*		N	X	X	X			
Centrarchidae								
rock bass, *Ambloplites rupestris*		I			X			X
green sunfish, *Lepomis cyanellus*		I		X	X	X	X	
pumpkinseed, *Lepomis gibbosus*		I			X	X		
bluegill, *Lepomis macrochirus*		I				X		
smallmouth bass, *Micropterus dolomieu*		I	X	X				

Table 1. Continued.

Family Common name, *Genus species*	Species of concern[a]	Origin[b]	Primary habitats[c] Yellowstone River	Powder River	Tongue River	Large prairie streams	Small prairie streams	Cold water habitats
Centrarchidae								
largemouth bass, *Micropterus salmoides*		I		X				
white crappie, *Pomoxis annularis*		I		X				
black crappie, *Pomoxis nigromaculatus*		I		X				
Percidae								
yellow perch, *Perca flavescens*		I		X				
sauger, *Sander canadensis*	MT	N	X	X	X	X		
walleye, *Sander vitreus*		I	X		X			

[a]MT = Species of concern in Montana; WY = Species of concern in (Montana Natural Heritage Program 2004; Wyoming Natural Diversity Database 2005)
[b]N = Native; I = Introduced (Brown 1971; Holton and Johnson 2003; Baxter and Stone 1995)
[c]Habitats in which the species has been captured, although each species may occasionally be found in other habitats (Brown 1971; Elser et al. 1980; Patton et al. 1998; Holton and Johnson 2003)
[d]There is just one record of brook stickleback in the Tongue and Powder river basins. The record was from Locate Creek, a tributary of the Powder River in Montana (Elser et al. 1980)

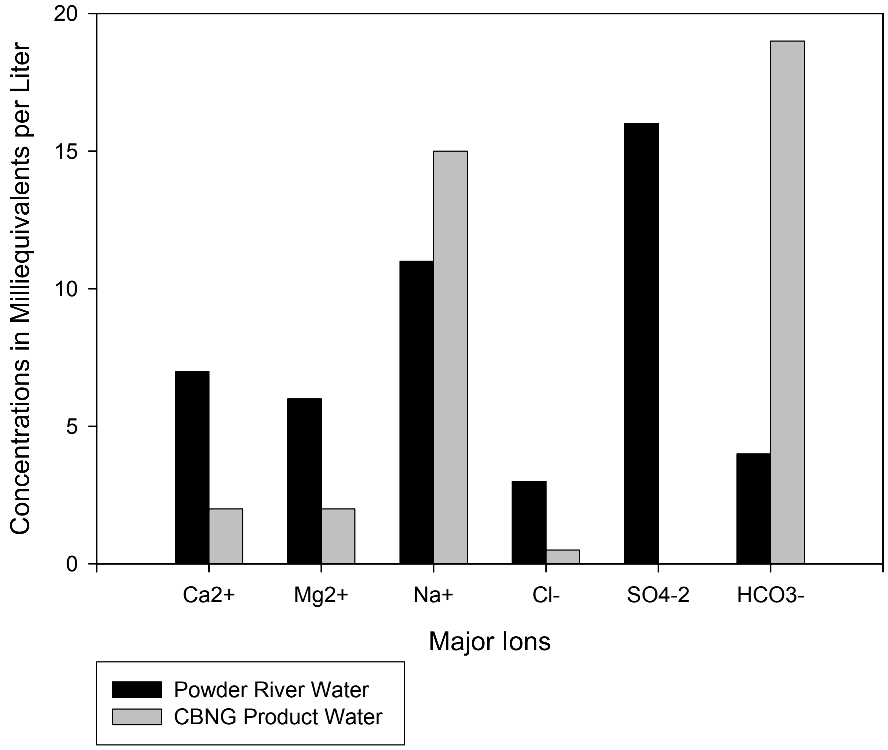

Figure 1. Major-ion chemistry of samples from the Powder River at Arvada, Wyoming, July 21, 1999 and CBM well 441451105375501, June 18, 1999 (Figure modified from Clark et al. 2001).

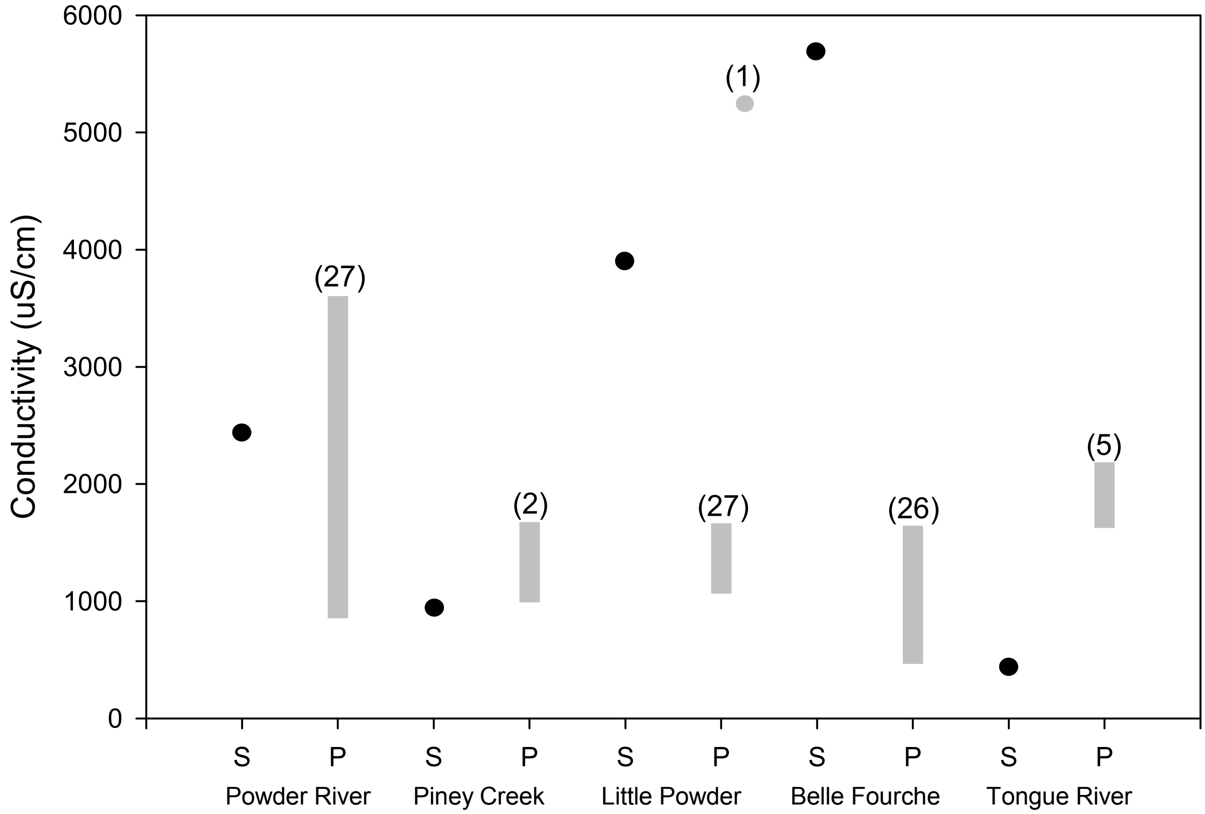

Figure 2. Comparison of conductivity measured in surface waters versus coalbed natural gas product water in drainage basins of the Powder River geologic basin. S = Surface water, P = product water; black dots represent medians of U.S. Geological Survey surface water data, gray bars represent ranges of product water values from the same drainage basin (with sample sizes in parentheses). Gray dot is a single outlier value from the Little Powder drainage basin. Data are from Clearwater et al. (2002)