EFFECTS OF COALBED NATURAL GAS DEVELOPMENT ON FISH ASSEMBLAGES IN TRIBUTARY STREAMS IN THE POWDER RIVER BASIN, MONTANA AND WYOMING

by

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DEDICATION

This thesis is dedicated to Cathy Klinesteker who always finds the energy and creativity to make great things happen. She showed me the kind of life I want to live and inspired me to take the lead.

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My family and friends also deserve recognition for their unwavering support. My mother encouraged me to always be positive because that is how you make good things happen. The Blanton family put a roof over my head, miles under my feet, and never let me take things too seriously.

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ABSTRACT

The Powder River Basin in Wyoming and Montana is undergoing the world's largest development of coalbed natural gas (CBNG) extraction. Potential exists for substantial effects on aquatic ecosystems because CBNG development involves production and disposal of large quantities of CBNG product water that differs from surface waters and alters natural flow regimes. In 2005 and 2006, I compared fish assemblages in streams with (treatment) and without (control) CBNG development, determined fish presence, growth, and survival in streams composed entirely of product water, and compared fish assemblages at multiple points above and below development to determine the effects of coalbed natural gas development on fish assemblages in the Powder River Basin. Some evidence suggested CBNG development had little or no effect on fish. For example, species richness and index of biotic integrity (IBI) scores were similar between developed and undeveloped sites, and no strong relationships existed between overall IBI scores or most IBI metric scores and the number or density of CBNG wells in a drainage area. Streams composed largely or entirely of product water were inhabited by reproducing populations of several species of fish. Other evidence suggested that CBNG may negatively affect fish assemblages over time. Conductivity was on average higher in treatment streams and was negatively related to biotic integrity. Bicarbonate, one of the primary salts in product water, appeared to be harmful to some species of fish. One salt-tolerant non-native species, northern plains killifish, was observed almost exclusively in treatment streams. The study was limited by a lack of pre-development data, unquantifiable product-water discharges, and because it was conducted during dry years. Potential effects of CBNG development may be more apparent during wet years when more sensitive fish assemblages are present. Monitoring efforts, development of a bicarbonate water quality standard, and efforts towards requiring complete product-water discharge reporting should continue.

INTRODUCTION

The Powder River Basin (PRB) in Wyoming and Montana is undergoing one of the largest coalbed natural gas (CBNG) developments. As of June 2006, 16,566 CBNG wells had been developed in the PRB in Wyoming (WOGCC 2007), and up to 70,000 more were projected over the next 20 to 30 years (Rice et al. 2000). Coalbed natural gas is formed in buried coal seams. Gas molecules are held in the coal seam by overlaying sediment layers and hydrostatic pressure. 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 migrates out of the spaces of the coal seam and moves up the well to be piped away (Wheaton and Donato 2004). The water that is pumped out of the coal seam is referred to as CBNG product water. CBNG product water differs chemically from surface waters, thereby creating the potential to affect aquatic ecosystems.

Water chemistry of CBNG product water is highly variable and is dependent on underlying geology. Moreover, water chemistry of CBNG product water may fluctuate as it reacts with soils and the atmosphere (Patz et al. 2004). However, general trends in conductivity and major chemical constituents exist. Water from coal seam aquifers is typically high in dissolved solids, particularly dissolved sodium (Na^{+}) and bicarbonate (HCO_3^{-}) ions, whereas surface waters in the PRB generally are high in dissolved calcium (Ca^{2+}), magnesium (Mg^{2+}), chloride (Cl^{-}), and sulfate (SO_4^{-2}) (Rice et al. 2000; Clearwater et al. 2002; McBeth et al. 2003) (Figure 1).

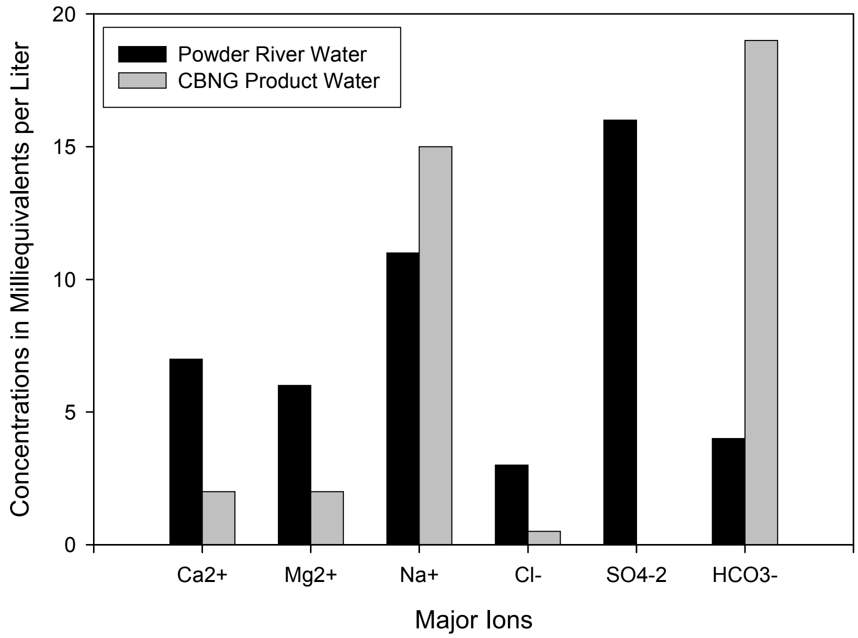

Figure 1.—Major-ion chemistry of the Powder River surface water at Arvada, Wyoming, July 1999 and CBNG product water from wellhead 441451105375501, June 1999 (Swanson et al. 2000).

The 16,566 producing CBNG wells in the Wyoming portion of the PRB collectively pumped about 215,500 m^3 of product water per day in June 2006, or enough to cover 21.6 hectares to a depth of 1 m (WOGCC 2007). Amounts of water produced vary among wells and generally decrease over time. However, total discharge from all wells increases as new wells are completed (Wheaton and Donato 2004).

Current management practices for the disposal of most CBNG product water in the PRB include direct discharge, discharge of treated water, or impoundment in on-channel or off-channel reservoirs. Direct discharge occurs when product water is delivered to a stream or an ephemeral channel. In other cases, product water is treated before discharge to surface waters to reduce concentrations of dissolved solids and ions

(ALL Consulting 2003). In-channel reservoirs use structures to create a barrier to flow in ephemeral or intermittent streams. Discharges of product water from in-channel reservoirs may 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. Whereas most water evaporates or infiltrates to deeper groundwater, 15-20% of water from unlined reservoirs may reach nearby stream channels by subsurface flow (ALL Consulting 2003).

Fishes native to the PRB have evolved life history strategies that allow them to survive in extreme conditions, but water development that alters flow regimes or water quality may result in changes in the fish assemblage (Hubert 1993). Few studies have specifically assessed how changes in water quality or water quantity associated with CBNG development affect fish in the PRB and the severity and direction of effects is unclear (Confluence Consulting, Inc. 2003; Confluence Consulting, Inc. 2004; Skaar et al. 2004).

Prior to my study, information on the effects of CBNG development on aquatic life was limited. More than 5 major basins are producing CBNG in the United States, but only the PRB and the Black Warrior Basin in Alabama produce a large volume of product water that is discharged to reservoirs or surface waters. In the PRB, five species of native fish were found upstream of CBNG development in Squirrel Creek, but no fish were found downstream of CBNG development (Confluence Consulting, Inc. 2003). However, CBNG development did not have a strong negative effect on fish assemblages in the Black Warrior Basin (O'Neil et al. 1991; Shepard et al. 1993). Surface discharge of product water altered water quality in streams in CBNG fields (O'Neil et al. 1991; Shepard et al. 1993). However, no significant decline in fish species diversity or biomass occurred after discharge of CBNG product water began (O'Neil et al. 1991; Shepard et al. 1993). Fish species differed in their response to CBNG discharge. Whereas the abundance of some fish species, such as the Gulf darter (*Etheostoma swaini*), decreased in the presence of product water, reproduction of the rough shiner (*Notropis baileyi*) was significantly greater downstream of product-water discharge (O'Neil et al. 1991). These effects suggested that the aquatic system was changing and that long periods of CBNG product-water discharge may result in changes in community composition (O'Neil et al. 1991).

Acute toxicity of CBNG product water from the PRB has been found in both laboratory and field settings. Sodium bicarbonate ($NaHCO_3$), the major salt associated with CBNG product water in the PRB, reduced hatch rates and survival of fathead minnows (*Pimephales promelas*) and pallid sturgeon (*Scaphirhynchus albus*)(Skaar et al. 2004). Concentrations of $NaHCO_3$ are typically greater than 400 mg/L and in some cases greater than 1,400 mg/L in product water in the PRB (Bartos and Ogle 2002, Clearwater et al. 2002; Forbes 2003). Hatch rate of fathead minnow eggs in 1,400 mg/L $NaHCO_3$ was only 43.9% whereas it was 62.5% in the control tank (Skaar et al. 2004). Post hatch survival rate was only 8.1% at $NaHCO_3$ concentrations of 1,400 mg/L compared to 94.3% in the control (Skaar et al. 2004). Survival of fathead minnows was significantly lower than in controls at all $NaHCO_3$ concentrations above 400 mg/L. The concentrations of $NaHCO_3$ that caused 50% mortality (LC-50) of 4-d old fathead minnows and pallid sturgeon were within the range of concentrations found in CBNG product water. However, older fathead minnows (39 d) and white suckers (22 d) were more tolerant of $NaHCO_3$ and the LC-50s for both were greater than 5,000 mg/L (Skaar et al. 2006). Similarly, mean instream 96-h survival rates of 2-d and 6-d post-hatch fathead minnows were 30% (range 11 to 49%) and 75% (range 73 to 75%), respectively (Farag et al. 2007). Because larval fish are sensitive to salts found in CBNG product water, release of CBNG product water to streams may result in reduced recruitment.

Chronic tests that assessed the potential long term effects of CBNG product water on growth, reproduction, and survival of fish also suggested that $NaHCO_3$ is harmful to fish. The survival of newly hatched fathead minnows in CBNG waters was 89% in the control and only 2.4% in 1400 mg/L $NaHCO_3$ at 37 d (Skaar et al. 2004). As $NaHCO_3$ concentrations and exposure times increased, the occurrence and severity of microscopic lesions increased in fathead minnows. Kidney damage was evident in fathead minnows exposed to 500 mg/L $NaHCO_3$ for 60 d (Skaar et al. 2006). The fathead minnow is typically more tolerant of salts than many other freshwater fish (Kochsiek and Tubb 1967; Mount et al. 1997). Therefore, toxicity of CBNG product water may be greater to other native fish species.

Surface disposal of the majority of CBNG product water requires permits for wastewater discharges that are subject to the National Pollution Discharge Elimination System (NPDES) permitting system and the regulations imposed by individual states. However, Montana and Wyoming do not have water quality standards for $NaHCO_3$. The NPDES permitting system considers general water quality parameters such as total dissolved solids (TDS) and conductivity. However, relative toxicities of different ions vary and general parameters such as TDS or conductivity do not account for particular ions or their combination (Mount et al. 1997). For example, mortality of fish in oil well brines was reached at salinity levels within their normal tolerance ranges, indicating the effects of an interaction among ions (Andreasen and Spears 1983). Therefore, established water quality limits may be less strict than necessary to protect biota.

Uncertainty existed concerning the potential effects of CBNG development on fish in the PRB. Whereas chloride was the primary cause for toxicity in product water in the Black Warrior Basin (O'Neil et al. 1991; Shepard et al. 1993), $NaHCO_3$ is the major salt in product water in the PRB. Sodium bicarbonate was detrimental to fish in the laboratory suggesting that existing water quality standards may not be sufficient (Skarr et al. 2004). Additionally, the effects of product water on fish assemblages in the arid environment of the PRB are not known and naturally intermittent streams may not provide the same opportunity for dilution as found in streams in the Black Warrior Basin. However, several species of fish were captured in streams receiving CBNG product water (B. Stewart, Wyoming Game and Fish Department, personal communication). Because limited baseline information existed, alterations of stream water quality and subsequent fish assemblage responses were unknown.

Coalbed natural gas development in the PRB has occurred predominately in Wyoming, but potential exists for substantial development in Montana (Figure 2). In 2003, the Montana Statewide Oil and Gas Environmental Impact Statement and Amendment of the Powder River and Billings Resource Management Plans analyzed the environmental impacts associated with the exploration and development of oil and gas resources including CBNG in the PRB (BLM et al. 2003). The Record of Decision allowed for changes in existing land use decisions. Lawsuits were filed against the Bureau of Land Management (BLM) Record of Decision and the U.S. District Court issued orders, dated February 25, 2005 and April 5, 2005, that required the BLM to analyze the cumulative direct and indirect environmental effects including relevant new information (BLM et al. 2006). Public comments on the deficiencies of the environmental impact statement included a general lack of knowledge about the existing aquatic resources and disregard for the potential impacts of changes in water quality on aquatic life. Sound scientific data were needed to understand the effects of CBNG development on aquatic ecosystems and create regulations that provide protection for aquatic life without unnecessary burdens to CBNG producers.

The goal of my study was to determine if CBNG development affected fish assemblages in tributary streams of the PRB. My specific objectives were to determine if 1) fish assemblages, water quality, or habitat were affected by the presence or amount of CBNG development within a drainage, 2) fish could live in streams composed entirely of CBNG product water, 3) areas in or below CBNG development in a drainage had lower species richness than expected, 4) fish assemblages changed immediately after CBNG development in a drainage, 5) fish assemblages at specific locations in the PRB changed after CBNG development, and 6) CBNG development affected fish growth and survival. I employed six different approaches to assess the local and large-scale effects of CBNG on fish assemblages of the PRB.

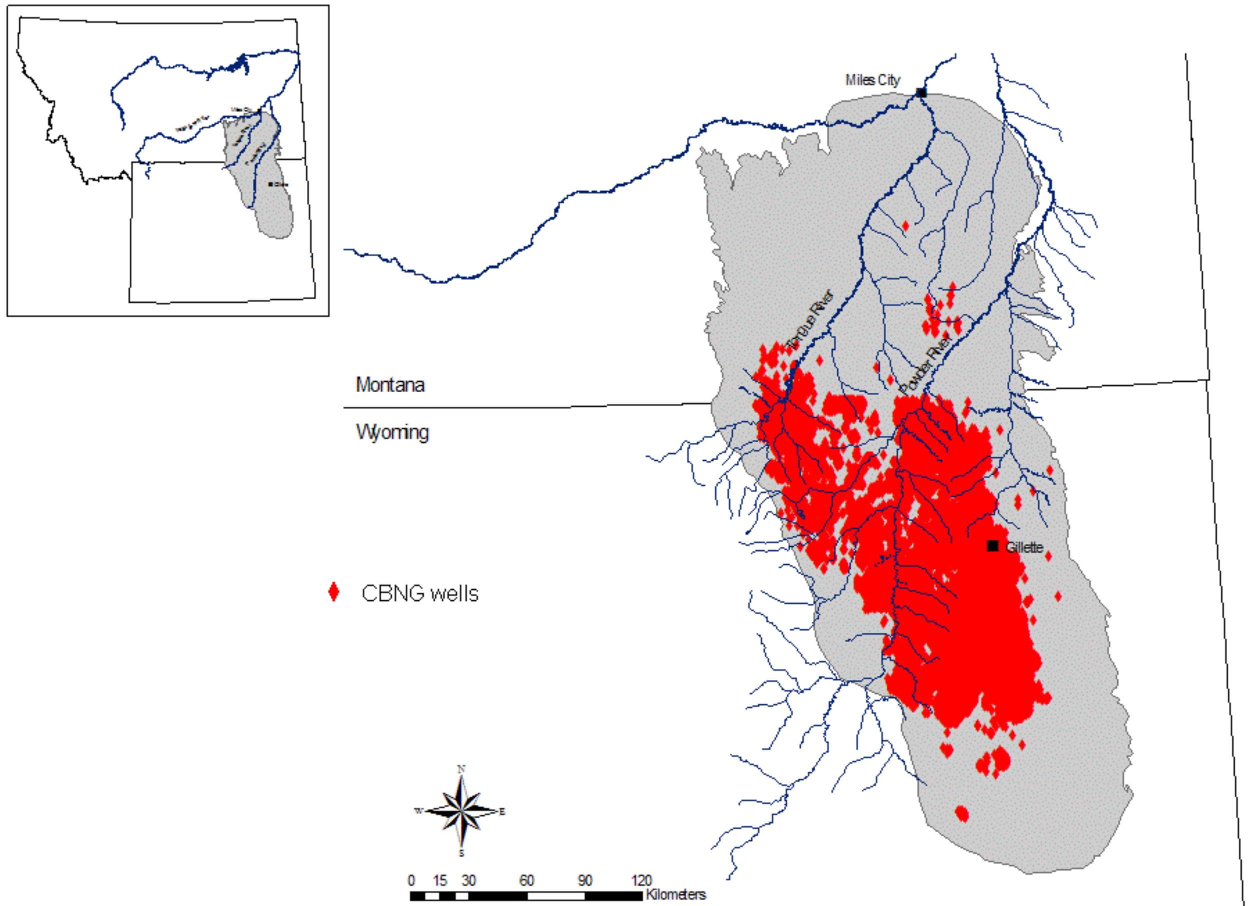

Figure 2.—Map of PRB showing the distribution of coalbed natural gas development and location of the Tongue and Powder rivers.

STUDY AREA

The PRB (PRB) is a geologic basin bounded by the Bighorn Mountains on the west and the Black Hills on the east and extends north from near Douglas, Wyoming, to Miles City, Montana (Figure 2). 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 located in the Northwestern Great Plains ecoregion (Woods et al. 2002; Chapman et al. 2004). 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 blue grama (*Bouteloua gracilis*), needle and thread grass (*Stipa comata*), and wheatgrass (*Agropyron sp*.), to shrubs including rabbitbrush (*Chrysothamnus sp*.), sagebrush (*Artemesia sp*.), and snowberry (*Symphoricarpos sp*.), to Rocky Mountain juniper (*Juniperus scopulorum*)-ponderosa pine (*Pinus ponderosa*) forests in the pine scoria hills. Riparian areas often contain deciduous woody vegetation including cottonwood (*Populus sp*.), boxelder (*Acer negundo*), and chokecherry (*Prunus virginiana*). 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).

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 hydrologic basin.

Streams of the PRB have headwaters in either montane or plains regions. 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 et al. 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 2,832 m^3/s at Moorhead, Montana, in 1923 (USGS 2005a), but also has 146 d on record when streamflow was 0 or less than 0.3 m^3/s (USGS 2005b).

The Tongue River hydrologic basin is 13,931 km^2 in area (Gustafson 2005). Elevation ranges from 3,059 m above sea level at the headwaters in the Bighorn Mountains to 719 m at the confluence with the Yellowstone River. The Tongue River is dammed near the Montana-Wyoming border and four lowhead irrigation diversion dams are located on the river between the Tongue River Dam and its confluence with the Yellowstone River. 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; discharge data for these three plains tributaries is lacking but they are intermittent.

The Powder River is the largest hydrologic basin in the PRB; its drainage basin area is 34,318 km^2 (Rehwinkle 1978). Elevation ranges from 3,950 m above sea level at the headwaters in the Bighorn Mountains to 676 m at the confluence with the Yellowstone River. 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 largely 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).

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). Cyprinids are most speciose, with 11 native and 3 introduced species, followed by catostomids with 8 native species. A total of eight fish species of concern occur in the Powder and Tongue river basins (Montana Natural Heritage Program 2007; Wyoming Natural Diversity Database 2005). Species of concern are native animals breeding in the state that are considered to be “at risk” due to declining population trends, threats to their habitats, or restricted distributions (Montana Natural Heritage Program 2007; Wyoming Natural Diversity Database 2005). Five species of concern occur in both large prairie streams and large rivers: goldeye (*Hiodon alosoides*), western silvery minnow (*Hybognathus argyritis*), shovelnose sturgeon (*Scaphirhynchus platorynchus)*, and sauger (*Sander canadensis*) (Wyoming Natural Diversity Database 2005). None of the nine species of concern has primary habitat in small prairie streams.

METHODS

Treatment Versus Control Stream Samples

To address objective 1, I compared fish assemblages in streams with CBNG development (treatments) and streams without development (controls) to determine if fish assemblages, habitat, or water quality were affected by CBNG development. Fish species richness, species presence and absence, and an index of biotic integrity (IBI; Bramblett et al. 2005) were compared between treatment and control streams. Also, IBI scores of fish assemblages were compared to the amount of CBNG development and the type of CBNG product-water management within each drainage. Habitat and water quality variables were compared between treatment and control streams. Additionally, I determined if relationships existed between specific water quality or habitat characteristics that were influenced by CBNG development and fish assemblages. Finally, regularity of fish recruitment was assessed to determine if fish were reproducing consistently in both treatment and control streams.

Site Selection

Treatment streams were defined as those that had some level of CBNG development within their drainages whereas control streams had no CBNG development in their drainage area. I identified a total of twelve treatment and twelve control streams in the study area. All streams were small prairie tributaries to the Tongue, Powder, or Little Powder rivers. However, control streams only existed in the Little Powder drainage because all streams in the Powder and Tongue were already developed for

CBNG. Most streams were located on private land and access could be secured only to eight treatment (Table 1, Figure 3) and eight control streams (Table 2, Figure 3).

I attempted to conduct fish sampling at three sites on each stream to obtain a spatial representation of fish assemblages. Each stream was divided longitudinally into three sections of equal length between its confluence with the Tongue, Powder, or Little Powder rivers and the uppermost reach of water (Sections A, B, and C moving from the confluence upstream). To determine the location of the uppermost reach with water in each stream I examined high resolution infrared aerial photos taken in July 2003 (WYGISC 2005). Sample locations within longitudinal stream sections were randomly selected. If randomly-selected locations could not be accessed to within 1 km with a vehicle, I chose the closest sampling location with vehicular access. If landowner permission was not granted, I sampled as close as possible to the randomly-selected location. At the vehicular access point, I first randomly selected the direction (i.e., upstream or downstream). I then randomly selected the location of the study reach by generating a random number between 150 and 300 and pacing that number of meters from the access point to the study reach. Finally, if the reach had no water present, I randomly determined by flipping a coin whether to move upstream or downstream to the nearest location that had water present. If no water was present anywhere in a stream section, I did not sample fish in that section. To preclude the influence of temporal variation within the sampling period, I randomly selected the sequence of stream sampling, and alternated between treatment and control streams.

Sites were sampled for fish, but not included in analyses if a lack of connectivity, rather than local stream conditions may have precluded fish from being present. Connectivity of two fishless treatment sites (B, C) on Middle Prong Wildhorse Creek could not be confirmed. Stream flows were historically minimal in the upper and middle reach of Middle Prong Wildhorse Creek (P. Dube, private landowner, personal communication). Product-water discharges have periodically increased water in Middle Prong Wildhorse Creek; however, the water quantity may not have been sufficient to allow fish to access the upper reaches of the stream. Therefore, sites B and C on Middle Prong Wildhorse Creek were not included in the analysis (Table 1).

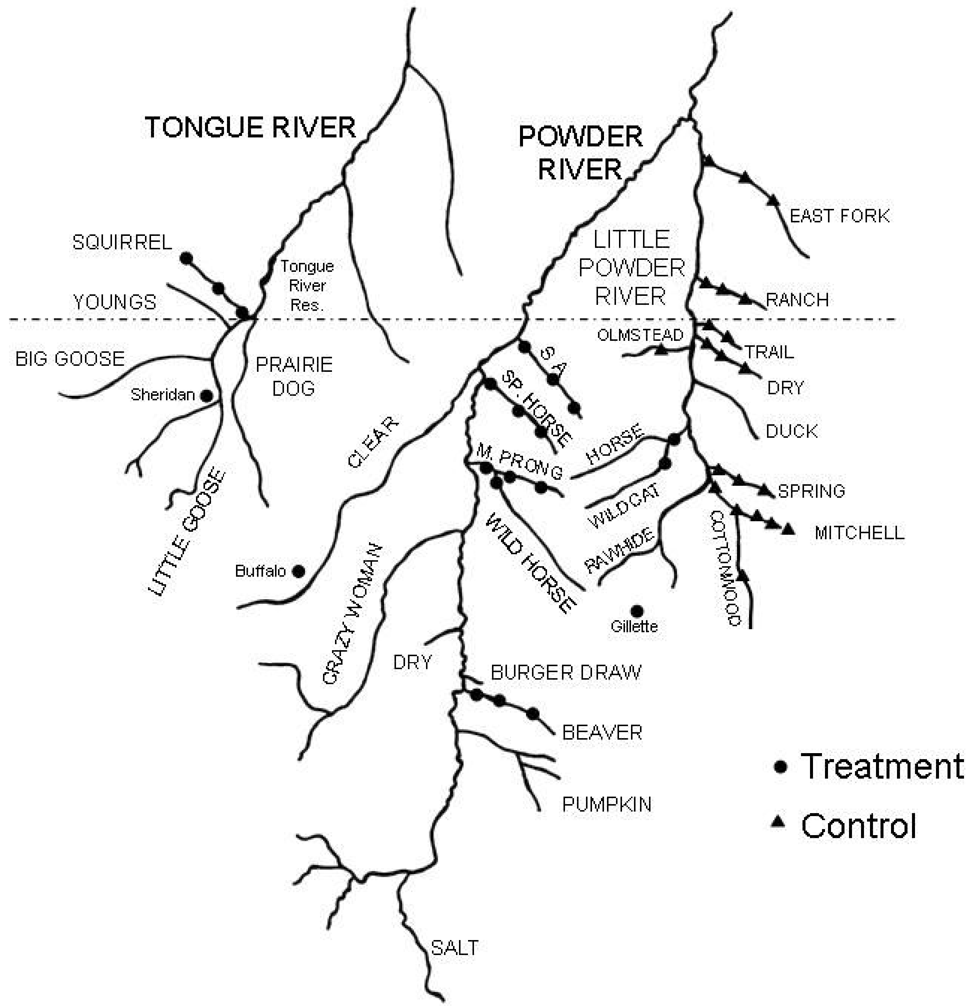

Figure 3.—Treatment and control sample locations

Table 1.—Treatment stream sample locations and dates in the Powder and Tongue river basins. Sample site (A-C) refers to longitudinal position on the stream with C being most upstream and A being furthest downstream.

Stream	Site	River km	Sample 2005	Sample 2006	Latitude (◦)	Longitude (◦)
Treatment						
Beaver Creek	A	0.9	*NA	27 July	44.11880	106.13273
	B	7.7	*NA	26 July	44.10111	106.05650
	C	12.3	*NA	26 July	44.08791	106.00106
Horse Creek	A	4.3	10 July	11 July	44.70834	105.41333
Middle Prong Wildhorse Creek	A	6.8	16 August	25 July	44.64736	106.04770
	B**	10.7	16 August	25 July	44.63665	106.01556
	C**	15.8	13 July	3 August	44.62906	105.94943
SA Creek	A	0.8	15 June	2 June	44.96875	105.92796
	B	5.8	17 June	2 June	44.90347	105.89311
	C	9.9	17 June	1 June	44.87515	105.85973
Spotted Horse Creek	A	0.5	16 August	1 June	44.84868	106.05375
	B	10.3	16 June	31 May	44.79589	105.96110
	C	16.4	17 June	31 May	44.76157	105.90939
Squirrel Creek	A	0.1	01 August	23 July	45.00479	106.85482
	B	6.7	31 July	23 July	45.03681	106.90661
	C	9.5	31 July	23 July	45.05109	106.92471
Wildcat Creek	A	0.5	10 July	11 July	44.69686	105.42502
Wildhorse Creek	A	0.4	16 August	25 July	44.63647	106.03394
	C	16.5	30 June	7 June	44.58694	105.12769

* Sites were not sampled because access was not granted. ** Sites were sampled but not included in analyses because they were fishless but their connectivity could not be confirmed.

Table 2.—Control stream sample locations and dates in the Powder river basin. Sample site (A-C) refers to longitudinal position on the stream with C being most upstream and A being furthest downstream.

Stream	Site	River km	Sample 2005	Sample 2006	Latitude (◦)	Longitude (◦)
Control						
Cottonwood Creek	A	0.1	12 July	9 July	44.61097	105.28865
	B	10.9	12 July	9 July	44.53476	105.22070
	C	15.6	12 July	9 July	44.49152	105.21144
Dry Creek (Little Powder)	A	2.4	06 July	10 July	44.94065	105.32389
	B	5.8	06 July	10 July	44.92405	105.29633
	C	17.0	06 July	10 July	44.87324	105.17925
East Fork Little Powder River	A	1.9	21 June	13 June	45.36782	105.29076
	B	12.9	21 June	13 June	45.31944	105.17152
	C	16.5	22 June	13 June	45.30901	105.13327
Mitchell Creek	A	0.9	11 July	7 June	44.53463	105.20974
	B	2.6	01 July	6 June	44.52647	105.19559
	C	5.7	01 July	6 June	44.51559	105.15924
Olmstead Creek	A	7.8	14 July	19 July	44.91689	105.44588
Ranch Creek	A	0.9	14 June	12 June	45.09317	105.31782
	B	9.5	14 June	12 June	45.05574	105.22366
	C	15.5	14 June	12 June	45.03767	105.15832
Spring Creek	A	0.9	09 June	8 June	44.63765	105.29952
	B	7.4	30 June	*NA	44.61273	105.22741
	C	16.5	30 June	7 June	44.58694	105.12769

* Sites were not sampled because access was not granted.

Field Sampling

Fish assemblages were sampled by seining following the Fish and Habitat Prairie Stream Survey Protocol (Appendix A) in 300-m stream reaches, which are sufficient to catch all the species present (Patton 1997). The species of each fish and total lengths (mm) of up to 100 randomly selected fish were recorded. Up to 10 voucher specimens per species were collected and preserved from each stream for laboratory verification and for placement into permanent voucher collections.

Stream habitat characteristics were recorded at each site at 11 longitudinally spaced cross-sectional transects and at 100 points along the thalweg (Lazorchak et al. 1998). Depth and substrate size were measured at five equally spaced points along each transect between the wetted edges of the stream. Substrates were classified according to size. The substrate size classes were bedrock (>4,000 mm), boulder (250 mm to 4,000 mm), cobble (64 mm to 254 mm), coarse gravel (16 mm to 64 mm), fine gravel (2 mm to 16 mm), sand (0.06 mm to 2 mm), fines (<0.06 mm), and hardpan (consolidated fine substrate <0.06 mm) (Lazorchak et al. 1998). Discharge was measured at each site with flowing water using a Marsh-McBirney flow meter in 2006.

Water quality was assessed at each site with field measurements and laboratory analyses. Stream temperature (^{o}C), specific conductivity (µmhos/cm), and dissolved oxygen (mg/L) were measured using a Yellow Springs Institute Model 85 meter. Turbidity (NTU) was measured using a LaMotte turbidimeter. Potential of hydrogen (pH) was measured using an Oakton pH Tester 2. In addition to field measurements, water quality samples were collected from the most downstream survey site on each stream in 2005 and from every site in 2006. All water samples were collected during a 1-week period in August to preclude temporal variation. Nutrient samples were preserved with sulfuric acid. All samples were kept on ice and delivered within 48 h to Energy Labs Inc., Billings, Montana, for complete ion analysis in accordance with American Public Health Association procedures (APHA 1998).

Data Analysis

An analysis of variance (ANOVA) model was used to test for significant differences of the means of fish, habitat, and water quality variables between treatment and control streams and to examine other sources of variation. A mixed linear model was fit to my data using the restricted maximum likelihood method in Mixed Model procedures of SAS Institute. The model incorporated two fixed effects and one random effect. The fixed factors and their levels were status of development (treatment, control) and year (2005, 2006). Individual streams were random components of the model that were nested within status of development. Thus, total variance for each metric was decomposed into the following factors: 1) Status of development, 2) Year, 3) Among streams within status of development, 4) All possible interactions and 5) Residual. Because a large proportion, i.e., 16 of the possible 24 small prairie streams in the PRB were sampled, a finite population correction factor ($\sqrt{(N\text{-}n/N\text{-}1)} = \sqrt{(24\text{-}16/24\text{-}1)} = 0.59$) was used to correct the probability (P-value) of obtaining my results given the null hypothesis ($H_0: \mu_{control} = \mu_{treatment}$) is true for all fish, habitat, and water quality comparisons (Kutner et al. 1996).

The assumptions of the ANOVA model were explored to determine whether ANOVA was appropriate for testing if the differences between treatment and control sites were significant. Some residuals were not normally distributed (Shapiro-Wilks test for normality, $P<0.05$) and did not meet the Levene's test for homogeneity of variance ($P<0.05$). However, because the departures of residuals from normality and homogeneity were small, and ANOVA is robust to departures from normality, these violations probably did not influence analyses (Zar 1984). Additionally, the benefit of using the parametric nested ANOVA to eliminate problems with non-independence of sample sites is greater than the cost of using a non-parametric test that does not allow nesting of variables. Significance was set at $\alpha = 0.05$ for all tests. All data analyses were conducted using SAS for Windows version 9.1.

The frequency of each fish species occurrence was used to determine if any species was relatively common in control streams but relatively rare in treatment streams, or vice-versa. Linear regression analysis was then used to determine whether a significant relationship existed between the abundance of those species and the water quality variables that had significantly higher or lower mean concentrations in treatment streams.

An IBI score for northwestern Great Plains streams was computed for each site (Bramblett et al. 2005). The IBI consists of 10 metrics and has a potential range of scores from 0 to 100 (Table 3). When fish abundance is low, IBI metrics are not statistically reliable and sites with few fish probably have low biotic integrity; therefore, sites with 1 to 10 individuals were assigned an IBI score of 10 (Bramblett et al. 2005). Sites with no fish received an IBI score of zero, and sites that were dry received no IBI score. Index of biotic integrity scores and individual IBI metrics were compared between treatment and control streams using the ANOVA model. Species richness was compared using an ANOVA model where the factors and their levels were status of development (treatment, control), stream position (A, B, C), and year (2005, 2006). Stream position was included to account for natural longitudinal variation in species richness (Vannote et al. 1980; Meador and Matthews 1992; Ostrand and Wilde 2002), but was not included in the analysis of IBI scores because the IBI score already accounts for stream position by adjusting for watershed area.

Treatment streams did not all have equal amounts of CBNG development. Databases containing the locations of CBNG wells were obtained from the Wyoming Geographic Clearinghouse (2007) and the Bureau of Land Management Miles City Field Office. The amount of CBNG development upstream of each site was determined by calculating the number of CBNG wells and well density (number of wells/km^2) within the watershed upstream of the sample point using ArcView 9.1 (ESRI 2006; Table 4). Regression analysis was used to determine whether a significant relationship existed between biotic integrity or its component metrics and the amount or density of CBNG development upstream of each sample site.

Product-water management varied among and within watersheds. I determined if fish assemblages responded differently to the types of product-water management upstream of the sampling sites. Databases of approved Wyoming Pollutant Discharge Elimination System (WYPDES) and Montana Pollutant Discharge Elimination System

(MPDES) permits for CBNG product water were acquired from the Wyoming and Montana Departments of Environmental Quality. Product-water outfalls were designated as discharges to on-channel reservoirs, off-channel reservoirs, or discharges to stream channels. Outfall type could not be classified for 3% of the entries in the WYPDES database, but these outfalls were included in the total number of outfalls. The total number, type, and density of outfalls within the watershed upstream of each sample site were determined using ArcView 9.1 (ESRI 2006; Table 4). Multiple regression analysis was used to determine whether a significant relationship existed between biotic integrity and the total number of product-water outfalls and the number of each type of outfall upstream of each sample site.

Water quality parameters, stream size, and substrate composition were compared between treatment and control streams using the ANOVA model. I also determined if fish assemblages responded to water quality or habitat. Regression analyses were used to determine whether a significant relationship existed between biotic integrity and water quality or habitat variables that had higher or lower mean concentrations in treatment streams than control streams. When the abundance and distribution of a species was sufficient, regression analysis was also used to determine whether a significant relationship existed between the species abundance and water quality variables.

The consistency of recruitment was assessed using length-frequency distributions. Insufficient abundances of individual species at most treatment and control sites precluded me from developing interpretable length-frequency histograms for all species at the site level. However, abundances were sufficient to create length-frequency histograms at three individual treatment sites.

Table 3.—Biological metrics of fish assemblages included in the northwestern Great Plains Index of Biotic Integrity and their hypothesized direction of response to human influence. Acronyms used in text, tables, and figures are given in the first column.

Metric category Acronym	Metric	Hypothesized direction of change with increasing human impact
Species richness and composition		
N_NatSp	Number of native species	Decrease
N_NatFam	Number of native families	Decrease
N_CatoIcta	Number of catostomid and ictalurid species	Decrease
P_Tol	Percent of tolerant individuals	Increase
Trophic composition		
P_InvCyp	Percent invertivorous cyprinid individuals	Decrease
N_BenInv	Number of benthic invertivorous individuals	Decrease
Reproductive guild composition		
P_LithOb	Percent of litho-obligate guild reproducers	Decrease
P_TolRep	Percent of tolerant reproductive guild individuals	Increase
Fish abundance and condition		
P_Native	Percent of native individuals	Decrease
N_NSpLL	Number of species with long-lived individuals	Decrease

Modified from Bramblett et al. (2005).

Table 4.—Summary of the amount of CBNG development and the product-water management for each treatment site.

Stream	Sample site	CBNG wells	(/km²)	Outfalls*	(/km²)	Outfalls to off-channel reservoirs	(/km²)	Outfalls to on-channel reservoirs	(/km²)	Outfalls to stream channels	(/km²)
Beaver Creek	A	820	(2.66)	144	(0.47)	10	(0.03)	101	(0.33)	32	(0.10)
	B	694	(2.55)	127	(0.47)	10	(0.04)	93	(0.34)	23	(0.08)
	C	566	(2.47)	102	(0.45)	10	(0.04)	68	(0.30)	23	(0.10)
Burger Draw	A	161	(4.47)	38	(1.06)	0	(0.00)	7	(0.19)	31	(0.86)
	B	102	(4.25)	35	(1.46)	0	(0.00)	5	(0.21)	30	(1.25)
	C	73	(4.56)	10	(0.63)	0	(0.00)	5	(0.31)	5	(0.31)
Dry Creek (Powder)	A	200	(3.03)	90	(1.36)	0	(0.00)	90	(1.36)	0	(0.00)
	B	180	(3.00)	86	(1.43)	0	(0.00)	86	(1.43)	0	(0.00)
	C	157	(3.20)	64	(1.31)	0	(0.00)	64	(1.31)	0	(0.00)
Horse Creek	A	3,138	(3.62)	300	(0.35)	4	(0.00)	226	(0.26)	59	(0.07)
Middle Prong Wildhorse Creek	A	519	(2.61)	130	(0.65)	2	(0.01)	89	(0.45)	35	(0.18)
	B	493	(2.59)	126	(0.66)	2	(0.01)	87	(0.46)	34	(0.18)
	C	387	(2.42)	91	(0.57)	2	(0.01)	66	(0.41)	22	(0.14)
SA Creek	A	732	(4.78)	140	(0.92)	12	(0.08)	86	(0.56)	37	(0.24)
	B	663	(5.10)	128	(0.98)	12	(0.09)	75	(0.58)	36	(0.28)
	C	627	(5.60)	125	(1.12)	12	(0.11)	76	(0.68)	34	(0.30)
Spotted Horse Creek	A	1,087	(4.25)	122	(0.48)	17	(0.07)	62	(0.24)	31	(0.12)
	B	989	(4.62)	109	(0.51)	8	(0.04)	59	(0.28)	33	(0.15)
	C	776	(4.41)	80	(0.45)	5	(0.03)	46	(0.26)	23	(0.13)
Squirrel Creek	A	161	(1.19)	0	(0.00)	0	(0.00)	0	(0.00)	0	(0.00)
	B	45	(0.39)	0	(0.00)	0	(0.00)	0	(0.00)	0	(0.00)
	C	12	(0.12)	0	(0.00)	0	(0.00)	0	(0.00)	0	(0.00)
Wildcat Creek	A	1,251	(2.59)	150	(0.31)	0	(0.00)	124	(0.26)	17	(0.04)
Wildhorse Creek	A	2,528	(3.80)	512	(0.77)	22	(0.03)	317	(0.48)	165	(0.25)

*Three percent of outfalls could not be classified.

Product-Water Stream Samples

To address objective 2, I sampled in formerly ephemeral streams that have been perennialized by CBNG product water to determine if fish can live in streams composed entirely of CBNG product water. These formerly ephemeral streams were not included in the comparison of treatments versus controls because a relevant control would be a dry and fishless streambed except during and following heavy precipitation. These streams were therefore considered separately. If no fish were captured in my sampling efforts, I placed native fish species in sentinel cages in the stream to determine if fish could live in CBNG product water.

Site Selection

Product-water streams were defined as formerly ephemeral draws that have been perennialized by the constant input of CBNG product water. I identified two product-water streams, Burger Draw and Dry Creek. Both streams are small tributaries to the Powder River (Table 5, Figure 4).

I conducted fish sampling at three sites on each stream to obtain a spatial representation of fish assemblages. Each stream was divided longitudinally into three sections of equal length between its confluence with the Powder River and the most upstream product-water outfall. Sample locations within longitudinal stream sections were randomly selected.

Field Sampling

Sites were sampled using the same protocol as the control and treatment samples. Sand shiners were collected by seining from the most downstream site on Burger Draw, and placed in the most downstream and the middle fishless site. Longnose dace were collected by seining Crazy Woman Creek and placed in the lower fishless site on Dry Creek. Every effort was taken to minimize handling and treat fish equally. Total length (mm) was recorded for each fish. Fish were acclimated for 30 min in transport tanks with source water added gradually to the transport tank (Piper et al. 1982). At the end of the acclimation period, 20 fish were placed in each of three sentinel cages (volume = 0.195 m^3, 0.635 cm wire mesh) at each site. Fish remained in the sentinel cages for 30 d. Sentinel cages were checked every 7 to 10 d and water quality parameters (conductivity, temperature, dissolved oxygen, pH, and turbidity) and mortalities were recorded on each visit. Total lengths (mm) of surviving fish were measured at the end of each exposure. At the termination of the test, all fish were euthanized with an overdose of MS-222.

Data Analysis

Species richness and an index of biotic integrity (Bramblett et al. 2005) score for northwestern Great Plains streams were computed for each site.

Table 5.—Product-water stream sample locations and dates in the PRB. Sample site (A-C) refers to longitudinal position on the stream with C being most upstream and A being furthest downstream.

Stream	Site	River km	Sample date 2005	Sample date 2006	Latitude (∘)	Longitude (∘)
Burger Draw	A	0.1	09 July	*NA	44.14814	106.14045
	B	1.9	09 July	*NA	44.14675	106.13448
	C	4.0	09 July	*NA	44.13281	106.10896
Dry Creek (Powder)	A	1.3	07 June	10 June	44.25848	106.16334
	B	2.6	19 June	10 June	44.25977	106.17370
	C	5.1	19 June	11 June	44.25246	106.19840

*Sites were not sampled in 2006 because access was not granted on private land.

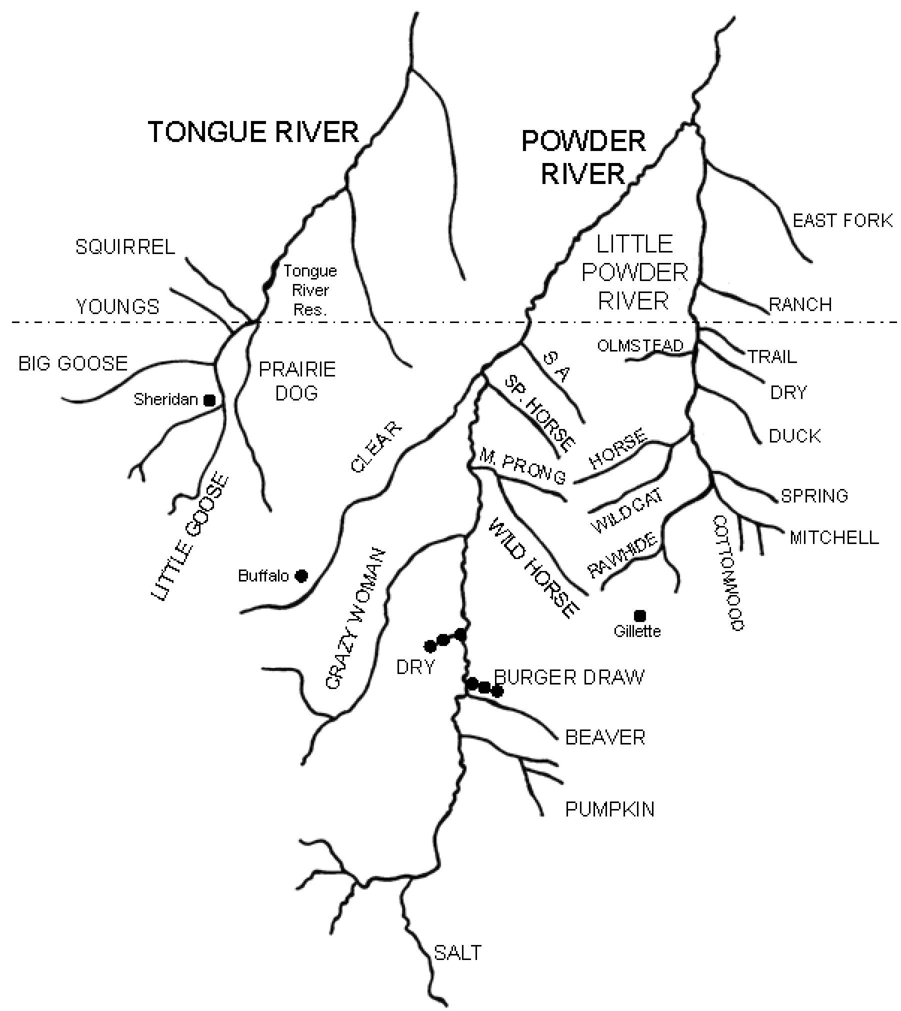

Figure 4.—Product-water stream sample locations.

Longitudinal Stream Surveys

To address objective 3, I compared the longitudinal distribution patterns of fish assemblages at multiple points on streams above and below CBNG development to determine if developed areas had lower species richness than expected. Species richness typically increases moving downstream from the headwaters to the confluence with a higher order stream (Harrel et al. 1967; Vannote et al. 1980; Mullen 2007). However, no fish species were captured in Squirrel Creek downstream of CBNG development whereas five native species were captured upstream of CBNG development (Confluence Consulting, Inc. 2003). If CBNG development occurs in the middle or lower reaches in a stream and if it affects fish, species richness may decline in lower reaches. I conducted fish surveys at five longitudinally distributed sites on each stream that had CBNG development only in the lower or middle reaches. I then examined the longitudinal distribution of species richness above and below development for deviations from expected patterns. If fish species were missing from reaches downstream of CBNG development, but present upstream, fish were placed in sentinel cages to determine if fish could survive in the downstream reach.

Site Selection

I identified three streams in which only a middle or lower reach was developed for CBNG (Table 6, Figure 5). To assess the longitudinal distribution of the fish assemblages, Squirrel and Youngs creeks were stratified into five sections between the confluence with the Tongue River and the uppermost reach of water (Sections A, B, C, D, E, moving from confluence upstream). Crazy Woman Creek was surveyed at five locations that were the locations of historic surveys (Patton 1997) and represented a longitudinal profile of the stream.

Field Sampling

Sites on Squirrel and Crazy Woman creeks were sampled using the same protocol as the methods for objective 1. However, abundant woody debris in Youngs Creek precluded seining. Single-pass electrofishing using a Smith Root backpack shocking unit and one netter was used as an alternative to seining in this stream. Single pass electrofishing in small prairie streams captures at least 90% of species present (Patton et al. 2000; Meador et al. 2003; Bertrand et al. 2006). Because samples from Youngs Creek were only compared among sites within the stream, the use of an alternative sampling technique that captures less than 100% of the species present did not affect the results. Methods used for sentinel cages were the same as the methods for *in-situ* growth and survival tests (see pg. 30).

Data Analysis

Longitudinal distribution of species richness was assessed to determine if the expected pattern of increasing species richness moving downstream existed. Patterns were considered unexpected when an upstream site had more species than the closest downstream site.

Table 6.—Longitudinal stream sample locations and dates in the PRB. Sample site (A-E) refers to longitudinal position on the stream with E being most upstream and A being furthest downstream.

Stream	Site	River km	Sample date	Latitude (◦)	Longitude (◦)
Crazy Woman Creek	A	1.2	20 July 2006	44.48382	106.13928
Crazy Woman Creek	B	18.9	20 July 2006	44.45884	106.29692
Crazy Woman Creek	C	23.4	20 July 2006	44.39812	106.36847
Crazy Woman Creek	*D	52.9	25 July 2006	44.20527	106.44999
Crazy Woman Creek	*E	69	24 July 2006	44.08779	106.53305
Squirrel Creek	A	0.1	23 July 2006	45.00479	106.85482
Squirrel Creek	B	1.6	23 July 2006	45.01176	106.85947
Squirrel Creek	C	6.7	23 July 2006	45.03681	106.90661
Squirrel Creek	*D	8.3	23 July 2006	45.04842	106.92218
Squirrel Creek	*E	9.5	23 July 2006	45.05109	106.92471
Youngs Creek	A	0.3	21 July 2006	44.96729	106.91341
Youngs Creek	B	2.3	24 July 2006	44.97966	106.92657
Youngs Creek	C	4.3	21 July 2006	44.99163	106.94909
Youngs Creek	*D	16.4	22 July 2006	45.05639	107.08456
Youngs Creek	*E	18.9	22 July 2006	45.04663	107.07048

* Sites were located upstream of CBNG development.

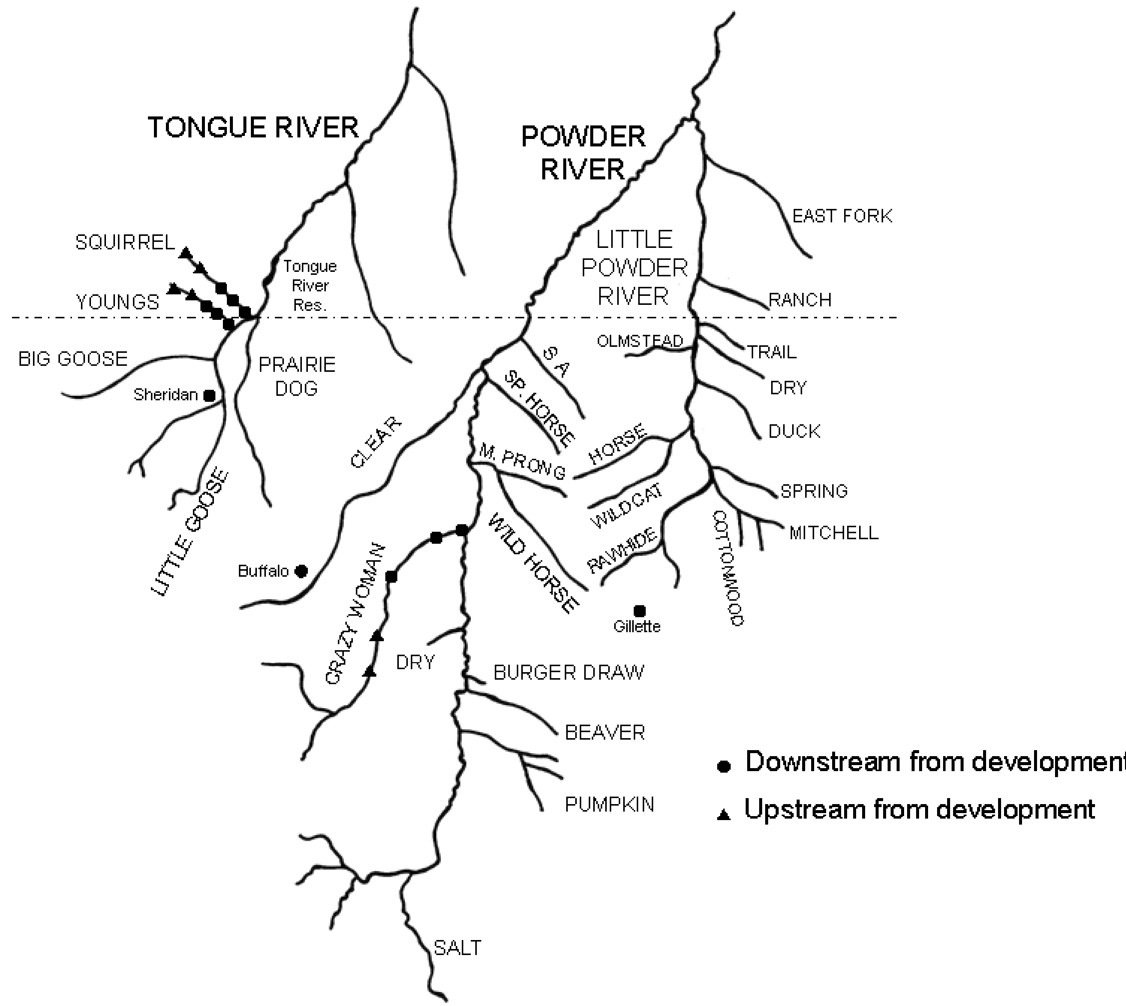

Figure 5.—Longitudinal stream survey locations.

Before and After Stream Surveys

To address objective 4, I compared fish assemblages before and after the initial development of CBNG to detect immediate changes in fish assemblages after development. The upper reach of Squirrel Creek was undeveloped in the summer of 2005, and development was projected to occur before the summer of 2006. In 2005, two sites were sampled using the prairie stream protocol (Appendix I). However, development did not occur before the 2006 sampling season. Therefore, this objective was omitted from my study.

Historical Comparisons

To address objective 5, I compared fish assemblages present during 2006 to fish survey data from the mid 1990s at locations on streams with and without CBNG development to determine if fish assemblages in developed areas have changed more than undeveloped areas. Re-sampling sites in areas of CBNG development and areas without CBNG development allowed me to determine if any differences in the fish fauna could be attributed to CBNG development. I compared fish species richness and IBI scores in 1994 to those in 2006 in areas that have since been developed (historical treatments) and in areas that have remained undeveloped (historical controls). I also examined changes in the distribution of species to determine if species increased or declined in relation to CBNG development.

Site Selection

Surveys conducted in 1994 (Patton 1997), prior to CBNG production, were repeated in the Wyoming portion of the PRB using similar sampling protocols. Seven tributaries to the Tongue and Powder rivers were re-sampled at 15 sites that have since been developed (historical treatments) and also at 5 sites that remain undeveloped (historical controls) (Table 7, Figure 6). Sites Salt Creek B and Clear Creek C were not re-sampled because access was denied; high stream flows from irrigation inputs precluded sampling at Prairie Dog Creek C.

Field Sampling

Township, range, and ¼ section locations from Patton (1997) were relocated to the closest ¼ section using a GPS unit. Sites were surveyed using the same protocol as the methods for objective 1. Although the reach lengths of Patton (1997) and Bramblett (Appendix I) differ slightly, both protocols are designed to capture 100% of the species present (Patton et al. 2000).

Data Analysis

Species richness and index of biotic integrity scores were calculated for surveys conducted in 1994 and for surveys conducted in this study. However, the number of long-lived species metric is based on fish total lengths. Because no fish length data existed for 1994 surveys, all IBI scores were calculated without the number of long-lived species metric. Final IBI scores were calculated by dividing the total of all metric scores by 9 rather than 10. Because shorthead redhorse and northern redhorse were identified as

Table 7.—Historical treatment and historical control sample locations and dates in the PRB. Sample site (A-E) refers to longitudinal position on the stream with E being most upstream and A being furthest downstream.

Stream	Sample site	River km	Sample date	Latitude (◦)	Longitude (◦)
Treatment					
Big Goose Creek	A	6.6	09 August 2006	44.86321	106.97561
Clear Creek	A	2.3	04 August 2006	44.87127	106.08238
Clear Creek	B	9	04 August 2006	44.83118	106.11735
Clear Creek	D	45.3	05 August 2006	44.61486	106.40936
Clear Creek	E	72.8	05 August 2006	44.43963	106.57907
Crazy Woman Creek	A	1.2	20 July 2006	44.48382	106.13928
Crazy Woman Creek	B	18.9	20 July 2006	44.45884	106.29692
Crazy Woman Creek	C	23.4	20 July 2006	44.39812	106.36847
Little Powder	A	55.1	09 June 2006	44.99371	105.34046
Little Powder	B	60.7	03 August 2006	44.94004	105.35474
Little Powder	C	66.9	10 June 2006	44.89074	105.37018
Little Powder	D	98.4	08 June 2006	44.63511	105.30298
Little Powder	E	121.5	03 August 2006	44.50800	105.45420
Prairie Dog Creek	A	1.8	12 July 2006	44.97610	106.83814
Prairie Dog Creek	B	12.1	12 July 2006	44.89630	106.85160
Control					
Big Goose Creek	B	22.4	08 August 2006	44.77425	107.04090
Crazy Woman Creek	D	52.9	25 July 2006	44.20527	106.44999
Crazy Woman Creek	E	69	24 July 2006	44.08779	106.53305
Little Goose Creek	A	7.4	07 August 2006	44.73730	106.94485
Salt Creek	A	0.1	06 August 2006	43.68939	106.33565

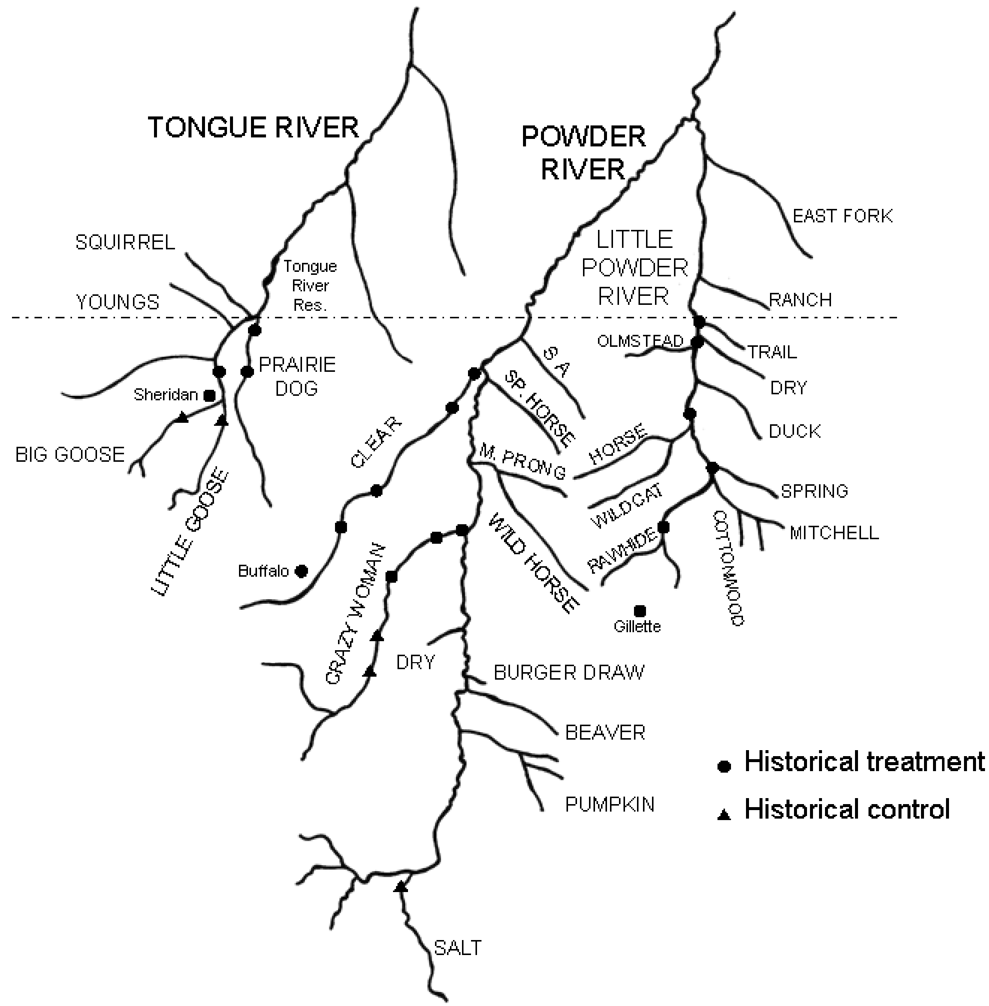

Figure 6.—Historical comparison sample locations.

separate species in 1994 surveys, but are now considered the same species (*Moxostoma macrolepidotum*), abundance data for shorthead redhorse and northern redhorse observations were combined for analysis.

The change in species richness (Δ SPRI=1994 SPRI-2006 SPRI) and the change in IBI score (Δ IBI=1994 IBI-2006 IBI) were calculated for each site. Changes at developed and undeveloped sites were compared using t-tests (Kutner et al. 2005). Species richness and IBI scores from 1994 and 2006 were compared at developed and undeveloped sites using two-sample t-tests (Kutner et al. 2005). The amount of CBNG development upstream of each site was determined by calculating the number of CBNG wells and well density (number of wells/km^2) within the watershed upstream of the sample point using ArcView 9.1 (ESRI 2006). Regression analysis was used to determine whether a significant relationship existed between the change in biotic integrity (Δ IBI) and the amount of CBNG development upstream of each sample site. Fish species presence and absence in 1994 and 2006 were compared to determine if fish assemblages changed at sites with and without CBNG development.

In-Situ Growth and Survival Tests

To address objective 6, native fish were placed in a series of sentinel cages in treatment and control sites to determine if CBNG product water affects fish growth and survival *in situ*. Lengths and survival were compared between treatments and controls after 30 days.

Site Selection

Sites were chosen using a random sample of sites that had sufficient water depth (>0.25 m) for cage placement. Two treatment (SA Creek-A, Dry Creek (Powder)-A) and three control sites (Dry Creek (Little Powder)-A, Mitchell Creek-A, Spring Creek-A) were selected.

Field Protocol

Three sentinel cages (volume = 0.195 m^3, 0.635-cm wire mesh) were placed about 15 m apart at each site. Longnose dace were collected by seining from Crazy Woman Creek and transported in aerated tanks to each site. Every effort was made to minimize handling and treat fish equally. Total length (mm) was recorded for each fish. I attempted to use fish longer than 55 mm to reduce escapement from cages. However, I did not collect enough large fish and the fish deployed last were on average shorter than the fish deployed first. Fish were acclimated for 30 min in transport tanks with source water added gradually to the transport tank (Piper et al. 1982). At the end of the acclimation period, 20 fish were placed in each of three sentinel cages at each site. Fish remained in the sentinel cages for 30 d. Sentinel cages were checked every 7 to 10 d and water quality parameters (conductivity, temperature, dissolved oxygen, pH, and turbidity) and mortalities were recorded on each visit. Total lengths (mm) of surviving fish were measured at the end of each exposure. At the termination of the test, all fish were euthanized with an overdose of MS-222. However, four of five 30-d tests were disrupted by lack of water, fish escapement, or cattle disturbance.

RESULTS

Treatment Versus Control Stream Surveys

Effects of CBNG Development on Species Richness

Mean species richness in control and treatment streams was not significantly different (Table 8, Figure 7). A total of 17 fish species was captured (Table 9). Fifteen species were captured in control streams, including 12 native and 3 non-native species. Thirteen species were captured in treatment streams, including 9 native and 4 non-native species. Plains minnow, longnose sucker, channel catfish, shorthead redhorse, and stonecat were captured exclusively in control streams. Lake chub and northern plains killifish were captured exclusively in treatment streams.

Most species were captured during fewer than 15% of the 68 sampling events; however, five native species were more ubiquitous. Creek chub, fathead minnow, longnose dace, sand shiner, and white sucker were each captured during at least 15% of the sampling events. Fathead minnow and white sucker were both captured at similar percentages of control and treatment sampling events (Figure 8). Creek chub were captured in a smaller percentage of controls than treatments (Figure 8). Sand shiner and longnose dace were captured in a larger percentage of control samples than treatment samples (Figure 8). No fish were captured in 5 percent of treatment and 8 percent of control samples.

Table 8.—Analysis of variance summary table for fish species richness of control and treatment streams of the PRB. Standard ANOVA acronyms define sum of squares (SS), degrees of freedom (df), mean square (MS), f-statistic (F), and the probability that the true means are equal (*P*-value).

Source of variation	Type III SS	df	MS	F	*P*
Status	4.89	1	4.89	0.76	0.26
Position	11.32	2	5.66	0.89	0.41
Year	2.63	1	2.63	0.41	0.52
Status * position	3.16	2	1.58	0.25	0.78
Status * year	0.04	1	0.04	0.01	0.94
Position * year	6.04	2	3.02	0.47	0.63
Status * year * position	3.54	2	1.77	0.28	0.76
Error	370.93	58	6.39		

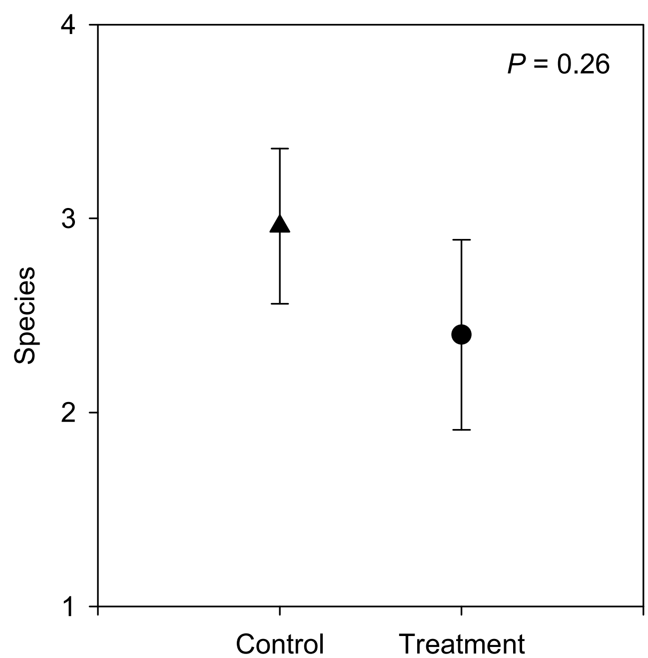

Figure 7.—Least squares mean species richness by status of development (control (▲) and treatment (●) sites). Error bars represent the standard error of the mean.

Table 9.—Species observed, percent occurrence, and the presence of species at control and treatment sites at sites that were included in analyses.

	% Samples		% Streams	
	Control (n=41)	Treatment (n=27)	Control (n=8)	Treatment (n=8)
Family				
Common name, *Genus species*				
Cyprinidae				
lake chub, *Couesius plumbeus*	0	7	0	25
common carp, *Cyprinus carpio**	5	15	25	38
brassy minnow, *Hybognathus hankinsoni*	10	26	13	38
plains minnow, *Hybognathus placitus*	2	0	13	0
sand shiner, *Notropis stramineus*	39	30	63	38
fathead minnow, *Pimephales promelas*	59	81	100	88
flathead chub, *Platygobio gracilis*	12	4	25	13
longnose dace, *Rhinichthys cataractae*	34	11	50	25
creek chub, *Semotilus atromaculatus*	17	33	38	50
Catostomidae				
longnose sucker, *Catostomus catostomus*	2	0	13	0
white sucker, *Catostomus commersonii*	29	26	38	50
shorthead redhorse, *Moxostoma macrolepidotum*	2	0	13	0
Ictaluridae				
black bullhead, *Ameiurus melas**	22	15	38	25
channel catfish, *Ictalurus punctatus*	7	0	13	0
stonecat, *Noturus flavus*	15	0	13	0
Cyprinodontidae				
northern plains killifish, *Fundulus zebrinus**	0	19	0	50
Centrarchidae				
green sunfish, *Lepomis cyanellus*s*	37	19	88	50

* Non-native to the PRB.

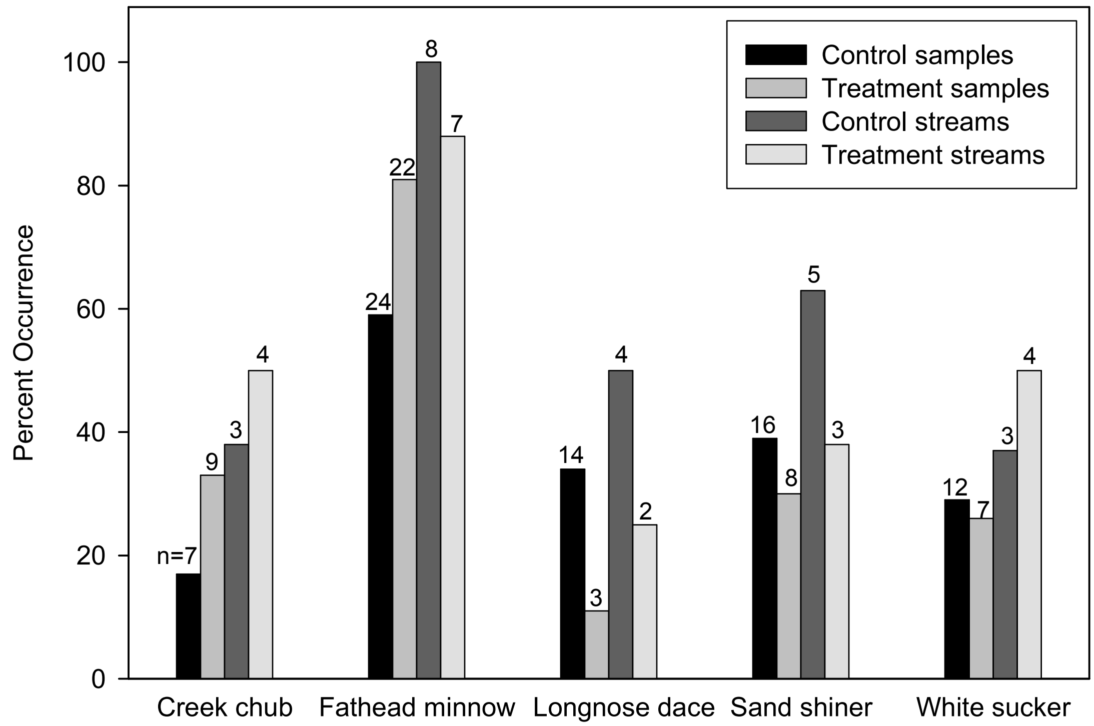

Figure 8.—Percent occurrence of the most ubiquitous native species in control and treatment samples and streams. Numbers above bars represent the number of samples or streams where the species occurred.

Effects of CBNG Development on Biotic Integrity

The mean IBI score of control streams was higher than of treatment streams, but the difference was not significant (Figure 9, Table 10). No significant difference existed between years. Index of biotic integrity scores were significantly different among streams within status of development ($P < 0.01$). No significant interaction existed between year and development status ($P = 0.84$). The means of seven of ten individual IBI metrics were higher in control streams than treatment streams, but not significantly so (Figure 10).

No relationship existed between IBI scores and the number or density of CBNG wells upstream of sample sites (Figure 11, Figure 12). The two treatment sites with the highest IBI scores were in relatively dense CBNG development on SA Creek (Figure 12). However, significant negative relationships existed between 4 of 10 individual IBI metrics and the number of CBNG wells including the number of native species, number of catostomid and ictalurid species, number of benthic invertivorous individuals, and the number of species with long-lived individuals (Figure 13). These relationships explained 22, 18, 19, and 23% of the variability among sites, respectively (Figure 13).

Product-water management did not appear to have a consistent effect on fish assemblages. No relationship existed between IBI scores and the number of product-water outfalls. Similarly, no relationship existed between IBI scores and the number of product-water outfalls discharged to on-channel reservoirs, off-channel reservoirs, or stream channels. Index of biotic integrity scores varied widely among sites with similar water management strategies. However, my quantification of product-water management did not accurately account for the quality or quantity of product water entering the stream.

Table 10.—Analysis of variance summary table for IBI scores of control and treatment streams of the PRB. Standard ANOVA acronyms define sum of squares (SS), degrees of freedom (df), mean square (MS), f-statistic (F), and the probability that the true means are equal (*P*-value).

Source of variation	Type III SS	df	MS	F	*P*
Status	894.12	1	894.12	1.49	0.25
Year	391.54	1	391.54	0.78	0.38
Year*status	21.10	1	21.10	0.04	0.84
Streams (status)	31430.86	14	2245.06	4.48	<0.01
Error	23058.16	46	501.26		

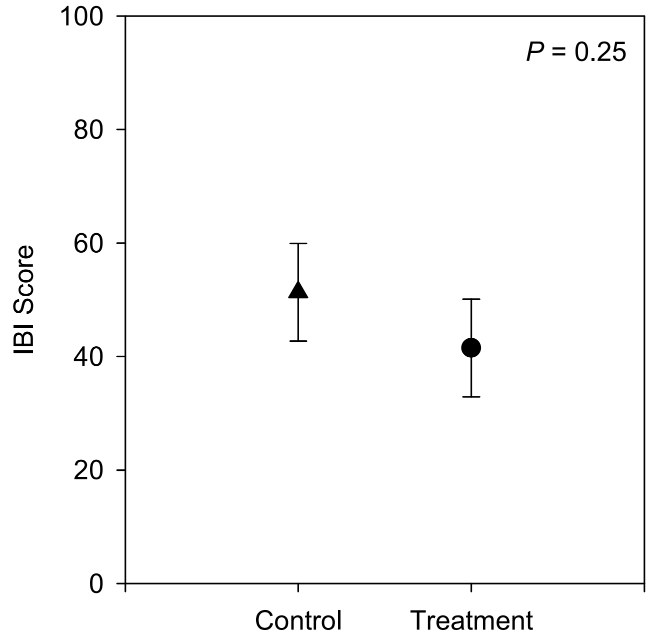

Figure 9.—Least squares mean IBI scores by status of development (control (▲) and treatment (●) sites). Error bars represent the standard error of the mean.

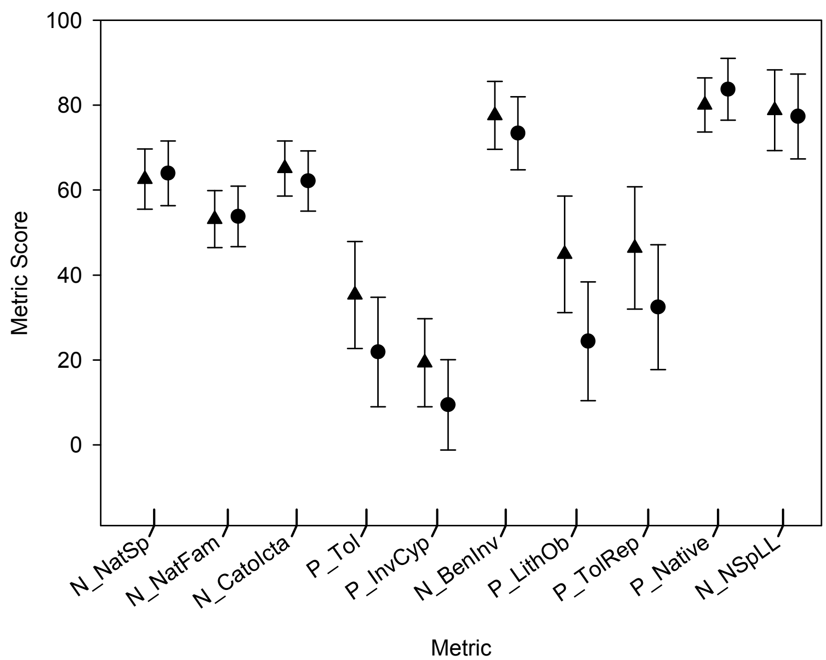

Figure 10.—Least squares mean IBI metric scores by status of development (control (▲) and treatment (●) sites). Error bars represent the standard error of the mean.

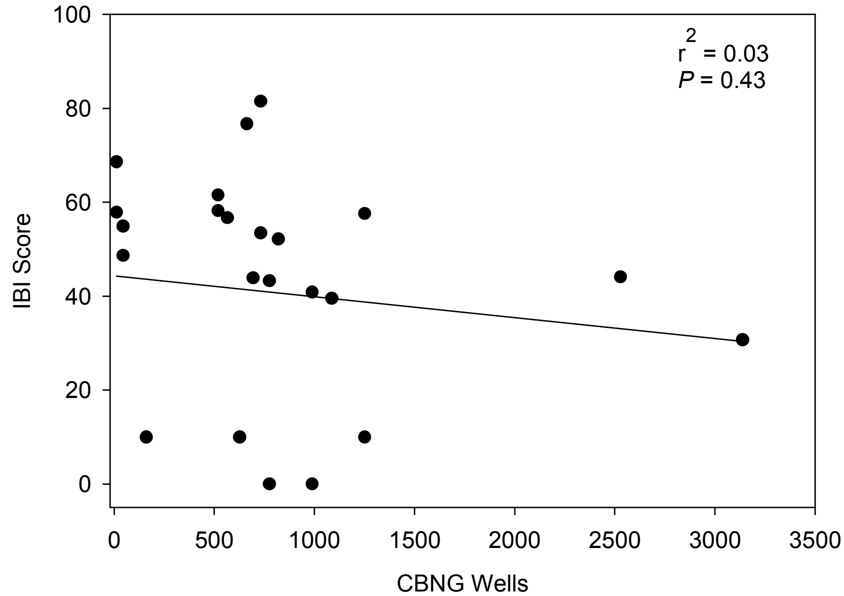

Figure 11.—Relationship between biotic integrity and the amount of CBNG development upstream of the sample site within the watershed.

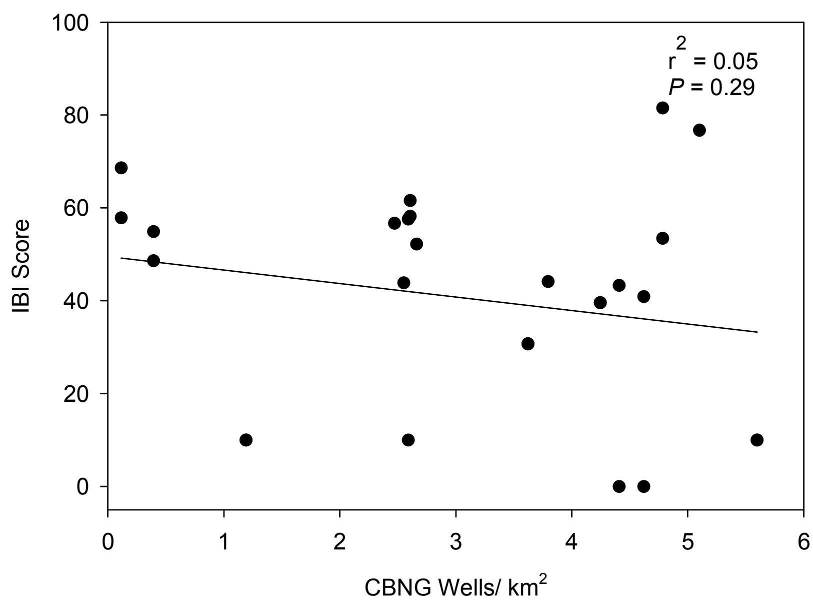

Figure 12.—Relationship between biotic integrity and the density of CBNG development upstream of the sample site within the watershed.

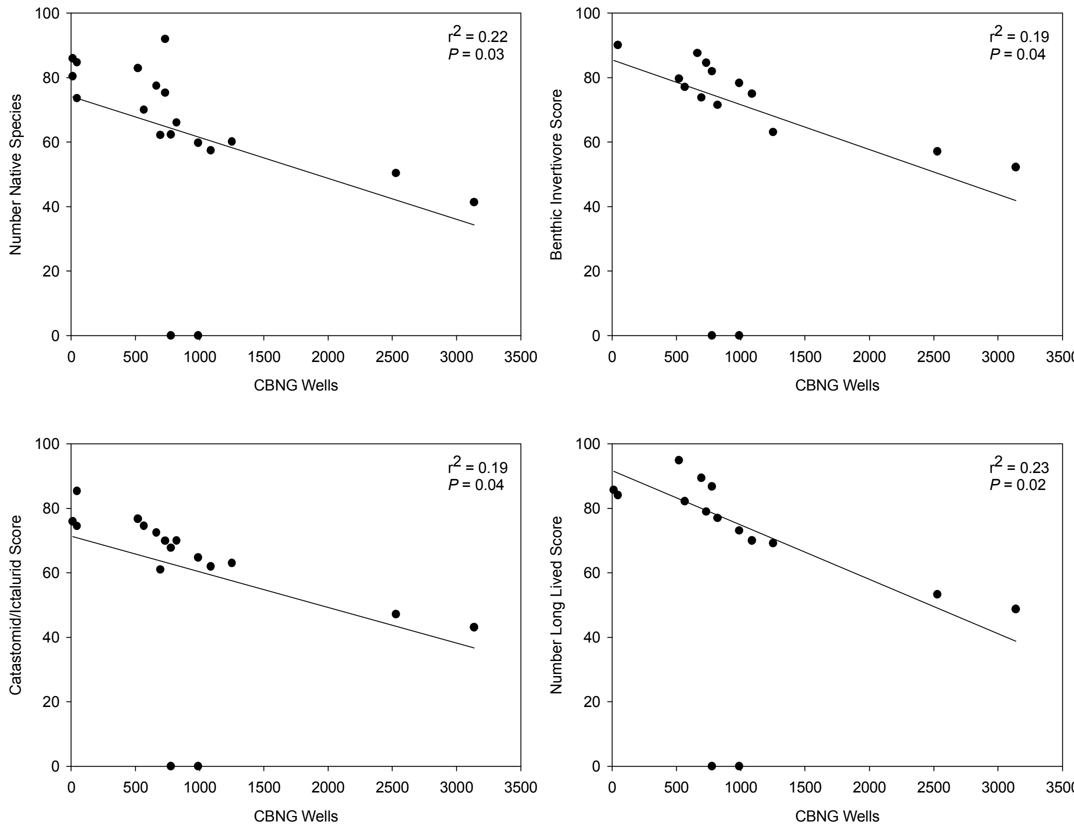

Figure 13.—Significant relationships between IBI metrics and the number of CBNG wells in the watershed upstream of the treatment sample site.

Relationships Between Water Quality and Fish Assemblages

Physical water characteristics were highly variable among sites within development status throughout the study area. No significant differences existed between treatment and control streams in either field (P = 0.15) or laboratory analyses (P = 0.50; Figure 15), but mean conductivity of treatment streams was more than 800 µmhos/cm greater than in control streams both in field observations and laboratory analyses. A significant negative relationship existed between IBI scores and conductivity (including both treatment and control sites) that explained 21% of the variability among sites (Figure 14).

Whereas physical characteristics were mostly similar between treatment and control sites, significant differences existed between treatment and control sites in specific ion and dissolved metal concentrations. Alkalinity ($CaCO_3^-$), bicarbonate (HCO_3^-), total dissolved solids, magnesium (Mg^{2+}), and sulfate (SO_4^{2-}) concentrations were significantly higher in treatment than control streams (all P<0.05; Figure 15). Sodium (Na^+) concentrations were also higher, but not significantly so, in treatment streams than control streams (Figure 15). Chloride (Cl^-) concentrations were significantly higher in control than in treatment streams (P<0.01; Figure 15). No relationship existed between IBI scores and the water quality variables that were significantly different between treatment and control streams. Index of biotic integrity scores tended to be lower in areas with higher concentrations of bicarbonate, but the relationship was not significant (P = 0.20; Figure 16). Only one nearly significant relationship existed between species abundance and the water quality variables that were significantly different between treatment and control streams. A negative relationship existed between longnose dace abundance and bicarbonate concentrations (P = 0.08) that explained 24% of the variability among sites (Figure 17). The longnose dace was one of the two ubiquitous species that occurred more frequently at control sites than at treatment sites. The other was the sand shiner, but no significant relationship existed between sand shiner abundance and water quality.

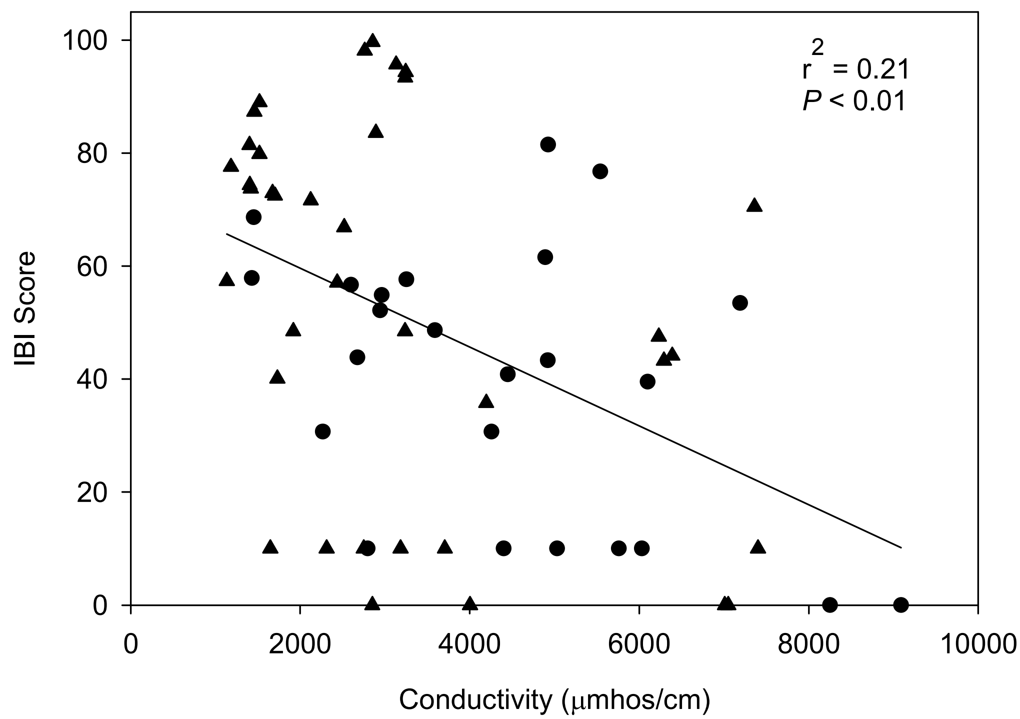

Figure 14.—Relationship between biotic integrity and conductivity (control (▲) and treatment (●) sites).

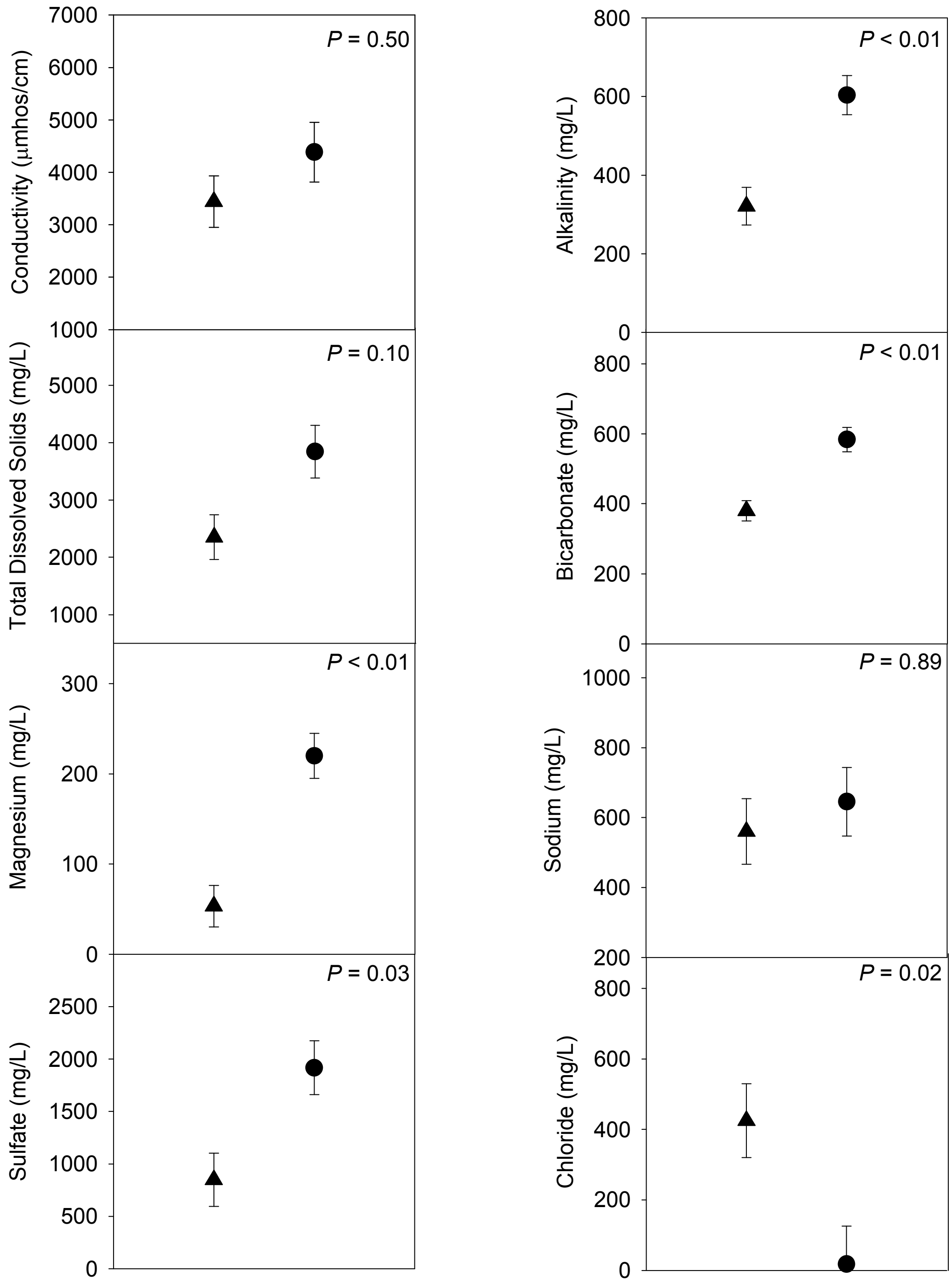

Figure 15.—Least squares mean water quality by status of development (control (▲) and treatment (●) sites). Error bars represent the standard error of the mean.

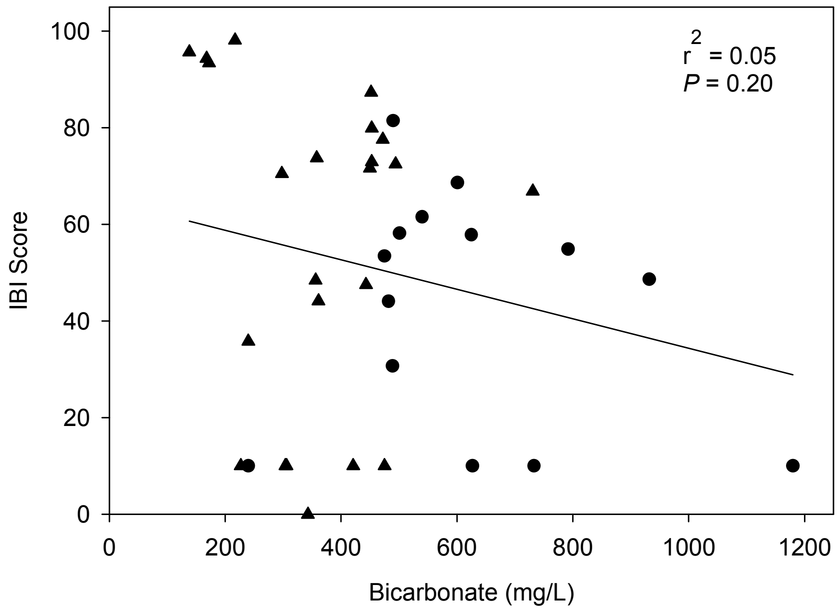

Figure 16.—Relationship between biotic integrity and bicarbonate (control (▲) and treatment (●) sites).

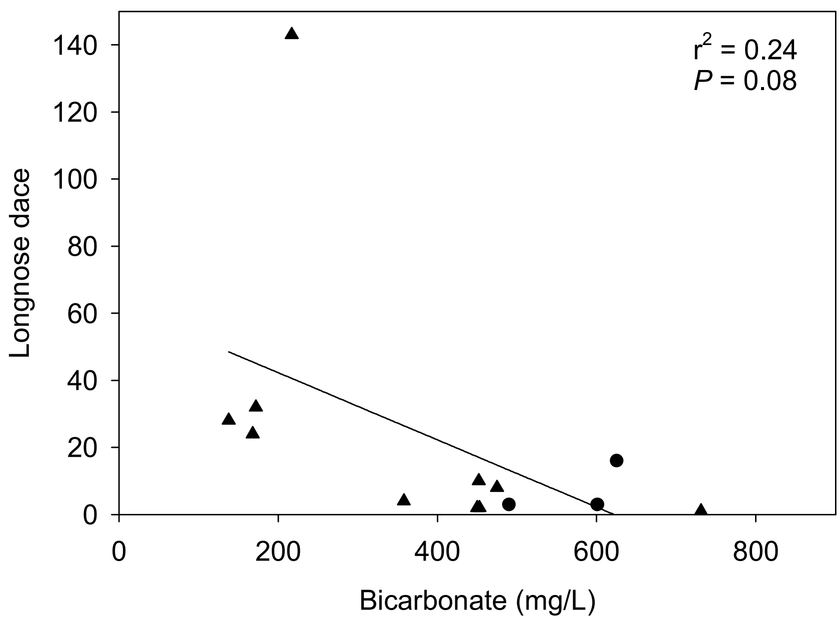

Figure 17.—Relationship between longnose dace abundance and bicarbonate (control (▲) and treatment (●) sites).

Relationship Between Development Status and Habitat

Most stream habitat characteristics of treatment and control streams were similar. Mean wetted width, depth, width to depth ratios, and discharge of treatments and controls were not significantly different (Figure 19). Watershed area of treatment streams was significantly larger than control streams (*P*=0.02, Figure 19). Biotic integrity was not positively correlated with watershed area because IBI scores are adjusted for watershed area (Figure 18). Streambed substrate composition was greater than 75% fine substrate in both treatment and control streams and not significantly different (*P*=0.70).

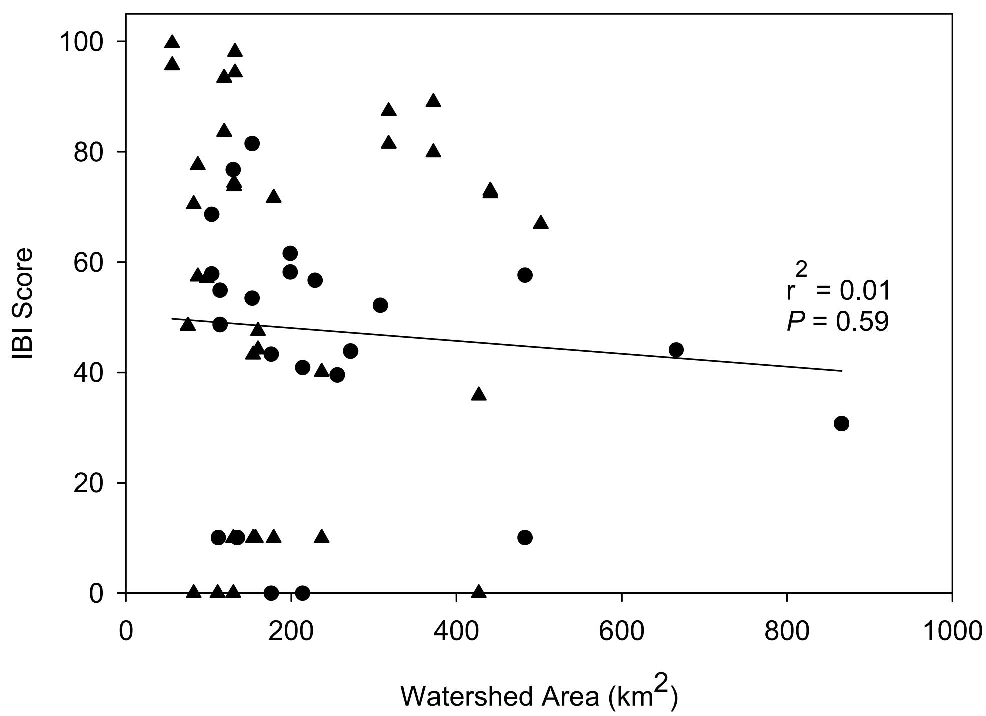

Figure 18.—Relationships between IBI scores and watershed area for control (▲) and treatment (●) sites.

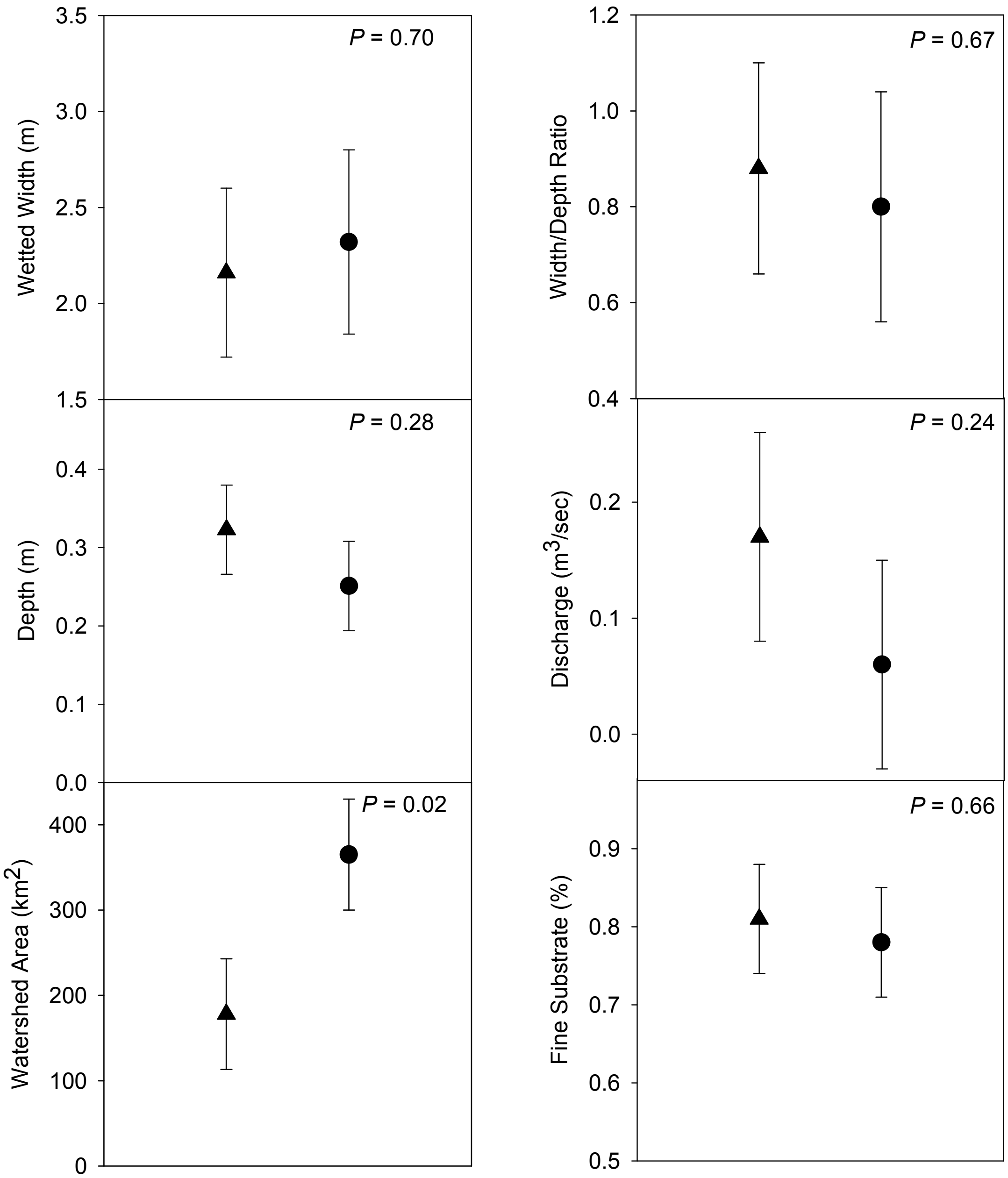

Figure 19.—Least squares mean stream size, discharge, and watershed area by development status (control (▲) and treatment (●) sites). Error bars represent the standard error of the mean.

<u>Recruitment in Treatment Streams</u>

Recruitment could not be assessed for most streams because fish abundances were too low to create effective length-frequency histograms (Miranda 2007). Sand shiner and fathead minnow abundances were sufficient at some sites in Beaver Creek to create length-frequency histograms. Sand shiners do not appear to be missing year classes at the most downstream site in Beaver Creek (Figure 20). Life expectancy for sand shiners is three years and age 1 (31-51 mm), age 2 (52-60 mm), and age 3 (> 61mm, Brown 1971) were all present. Fathead minnows also appear to have multiple year classes present at all sites on Beaver Creek, even though the most upstream site on the stream was directly below a product-water discharge (Figure 21). Life expectancy for fathead minnows is only two years and age 1 (38-51 mm) and age 2 (52-76) were both present (Brown 1971).

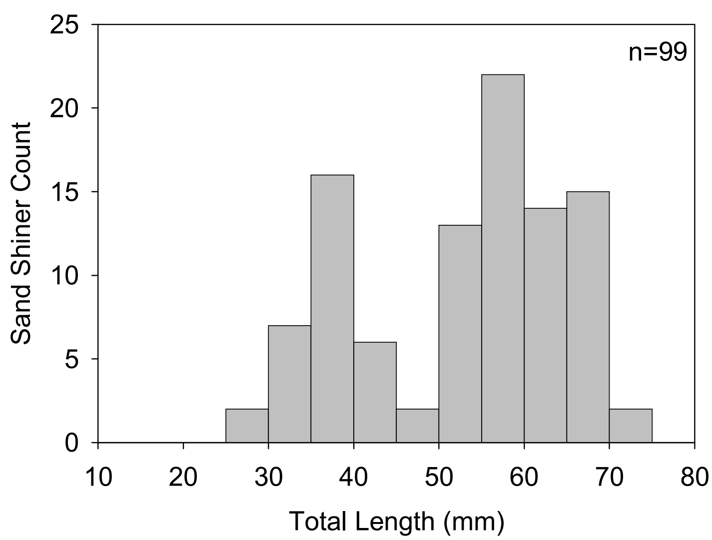

Figure 20.—Length frequency distribution of sand shiners at the most downstream site (A) on Beaver Creek.

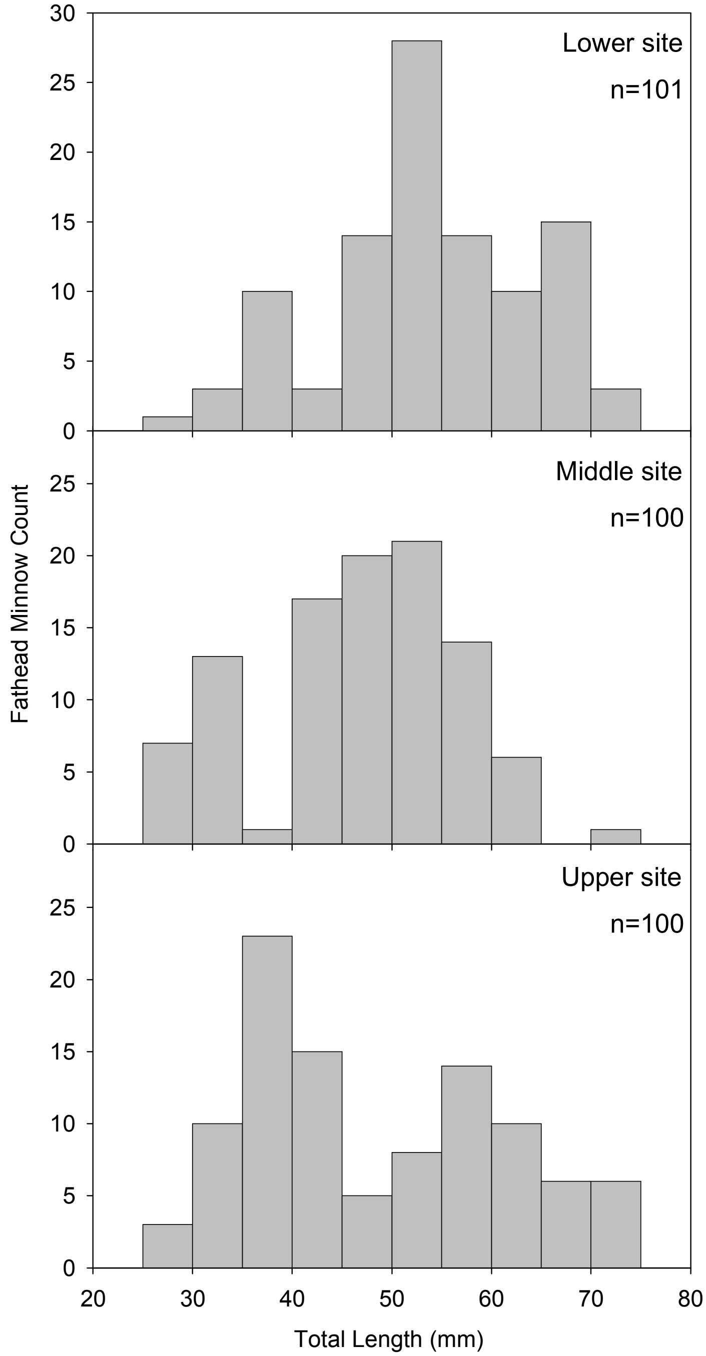

Figure 21.—Length frequency distributions of fathead minnow at all sample sites on Beaver Creek.

Product-water Streams

Fish were only captured in Burger Draw at the most downstream site. Species collected there were fathead minnow, flathead chub, sand shiner, river carpsucker (*Carpoides carpio*), black bullhead, and northern plains killifish. Beaver dams between the most downstream site and the middle site on Burger Draw likely precluded fish colonization from downstream. All sand shiners placed in cages at the most downstream site and the middle fishless site in Burger Draw survived for 30 d (Figure 22). Mean length of sand shiners in cages was similar between the most downstream site and the middle fishless site on day 30 (P = 0.45, Figure 22).

No fish were captured at sample sites in Dry Creek. However, a large (3.5 m) headcut barrier on Dry Creek 15 m above its confluence with the Powder River likely precluded fish colonization from downstream. Flathead chub and sand shiners were captured in Dry Creek below the headcut barrier. Flash flooding destroyed sentinel cages on Dry Creek.

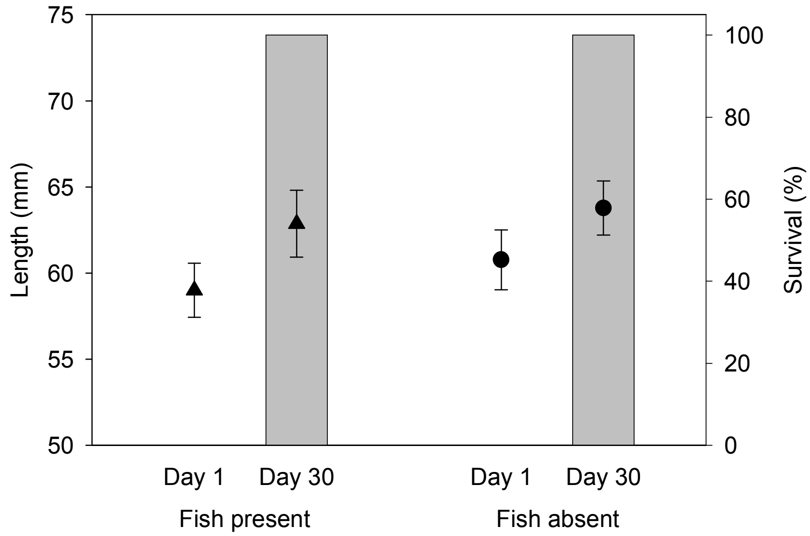

Figure 22.—Comparison of mean length (triangles and circles) and survival (bars) of sand shiners between the downstream site where sand shiners were captured (▲) and the middle site where no fish were captured (●) on Burger Draw. Error bars denote 95% confidence intervals.

Longitudinal Stream Surveys

Species richness did not increase from upstream to downstream as is commonly observed in prairie streams. Fewer species were observed at the most downstream sites than at some middle and upper sites in all three streams (Figure 23). For example, 3 to 5 species were present at the upstream sites in Squirrel Creek, but only single individuals of 2 species were collected at the most downstream site. To determine if fish could live and grow at the downstream site, longnose dace were collected from a site upstream of CBNG development in Youngs Creek in the Tongue drainage and placed in the most upstream and the most downstream sites on Squirrel Creek. Survival was 76% in the downstream site and 73% in the upstream site after 30-d exposures (Figure 24). Length of longnose dace was not significantly different between the upstream and downstream cages (P = 0.42, Figure 24). Lower sites had less water than upstream sites. However, the unusual patterns were likely caused by altered flow regimes in all three streams due to irrigation, beaver dams, or stock ponds.

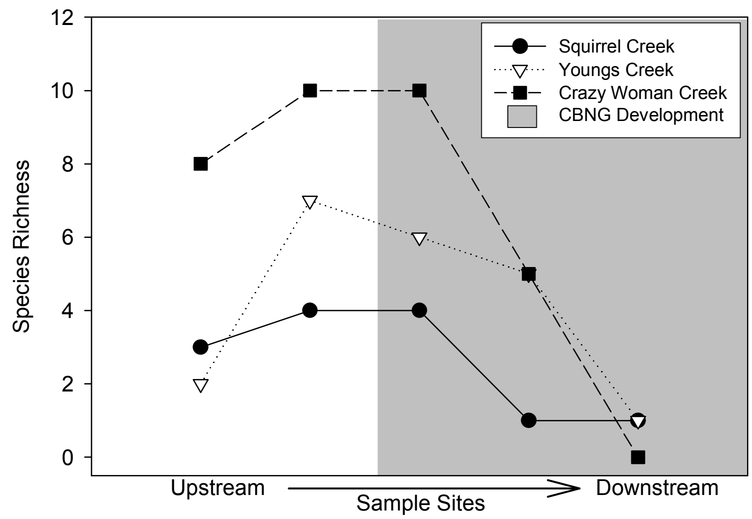

Figure 23.—Longitudinal distribution of species richness above and within CBNG development.

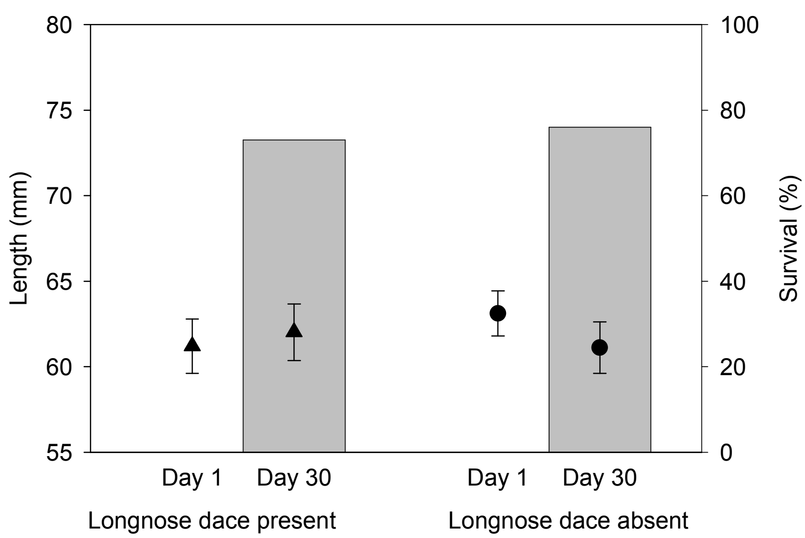

Figure 24.—Comparison of mean length (triangles and circles) and survival (bars) of longnose dace between the upstream site where longnose dace were captured (▲) and the downstream site where no longnose dace were captured (●) on Squirrel Creek. Error bars denote 95% confidence intervals.

Historical Comparisons

Changes in Species Richness

The mean change in species richness between 1994 and 2006 was not significantly different between historical treatment and control sites (P = 0.71, Figure 25, Table 11). The mean species richness in 1994 and 2006 was not significantly different at historical treatment sites (P = 0.24, Table 11) or control sites (P = 0.74).

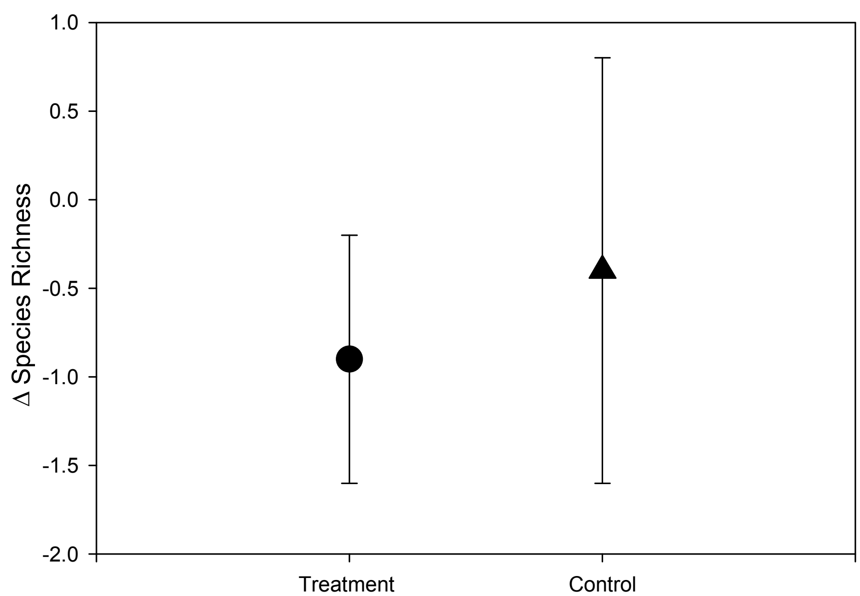

Figure 25.—Mean change in species richness between 1994 and 2006 at historical treatment and control sites. Error bars denote the standard error of the mean.

<u>Changes in Biotic Integrity</u>

The mean changes in IBI scores at historical treatment and control sites were not significantly different (*P* = 0.46, Figure 26, Table 11). The mean IBI score of the fish assemblages at historical treatment sites was significantly higher in 1994 than in 2006 (*P* = 0.004;Table 10). However, the mean IBI score of the fish assemblages at historical control sites was also significantly higher in 1994 than in 2006 (*P* = 0.05; Table 11). Three historical treatment sites were dry in 2006 and were not included in the analysis. Seventy-five percent of historical treatment and 100% of control sites had higher biotic integrity in 1994 than in 2006. No relationship existed between the change in IBI score and the number of CBNG wells in the drainage upstream of each site ($P = 0.50$; $r^2 = 0.025$).

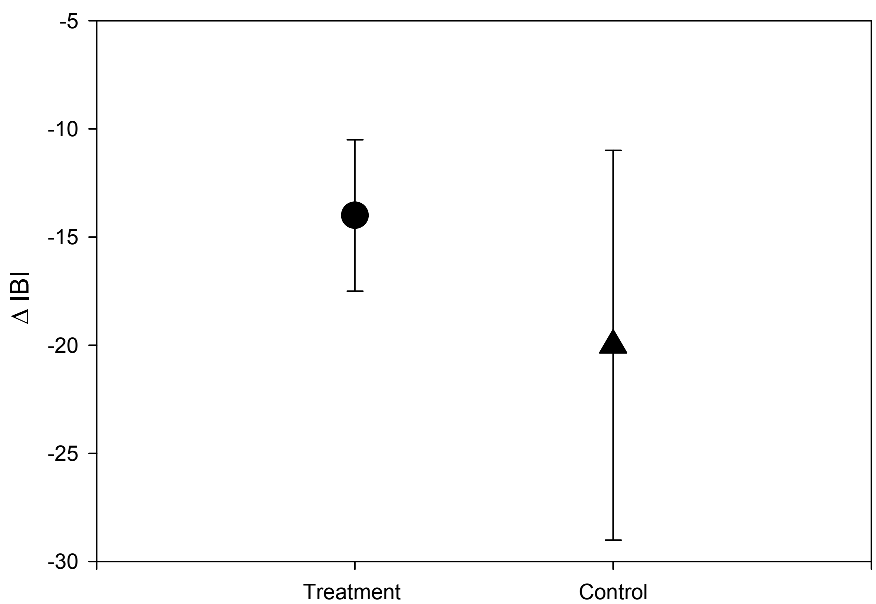

Figure 26.—Mean change in biotic integrity scores between 1994 and 2006 for historical treatment and control sites. Error bars denote the standard error of the mean.

Table 11.—Mean species richness (SPRI) and mean index of biotic integrity (IBI) scores in 1994 and 2006 by development status. Comparison of the mean change from 1994 to 2006 in species richness (Δ SPRI) and IBI score between historical treatment and historical control sites. Acronyms define sample size (N), standard deviation (SD), standard error (SE), and the probability that the true means are equal determined by a two-sample t-test (*P*-value).

Variable	Status	Year	N	Mean	SD	SE	Min	Max	*P*-value
SPRI	Treatment	1994	12	7.9	2.7	0.8	5	13	0.24
		2006	12	7.0	2.1	0.6	4	10	
	Control	1994	5	7.4	1.7	0.7	6	10	0.74
		2006	5	7.0	2.6	1.1	3	10	
Δ SPRI	Treatment		12	-0.9	2.6	0.7	-4	4	0.71
	Control		5	-0.4	2.5	1.2	-4	2	
IBI	Treatment	1994	12	78.1	8.2	2.4	58.5	88.7	*<0.01
		2006	12	64.0	12.6	3.6	42.7	81.1	
	Control	1994	5	87.3	11.4	5.1	68.4	96.5	*0.05
		2006	5	67.3	15.3	6.8	44.2	86.4	
Δ IBI	Treatment		12	-14.0	12.3	3.5	-35.1	4.8	0.46
	Control		5	-20.0	20.1	9	-51.7	-2.5	

* Statistically significant differences ($\alpha = 0.05$).

Changes in Fish Occurrences

No pattern existed between changes in fish distribution and CBNG development status (Table 12). Seven native fish species captured in 1994 were not captured in 2006. Five native species appeared to be missing from historical treatments and two from historical controls. Two native species not captured in 1994 were captured in 2006 in historical controls. Five non-native fish species captured in 2006 had not been captured in 1994, three in historical treatments and two in historical controls. However, most of the changes in species distributions were at 2 or fewer sites with low abundances suggesting that the observations may be a function of chance rather than widespread reduction or expansion of distributions (Table 12).

Table 12.—Changes in species sampled in historical treatment and control streams between 1994 and 2006.

Status	Species	# Sites	# Streams	# Individuals
	Captured 1994, Not captured 2006			
Treatment	brassy minnow	2	1	5
	lake chub	2	2	1
	plains minnow	2	2	7
	sturgeon chub	1	1	1
	western silvery minnow	1	1	**present
Control	goldeye	2	1	5
	plains minnow	1	1	45
	Captured 2006, Not captured 1994			
Treatment	*black bullhead	2	1	3
	*spottail shiner	1	1	6
Control	channel catfish	1	1	1
	river carpsucker	1	1	1
	*northern plains killifish	1	1	84
	*largemouth bass	1	1	8
	*brown trout	1	1	2

* Species not native to the study area.
** No number included in Patton 1997.

DISCUSSION

As of yet, it does not appear that CBNG development has had widespread and pervasive effects on fish assemblages in the tributary streams of the PRB. However, evidence suggests that there is potential for declines in biological integrity of streams over the lifetime of development. Moreover, limitations of my study may result in underestimation of the effects of development. I developed several recommendations to help compensate for the limitations of my study, better understand the biological systems, and assist in future management decisions.

Several factors indicate that CBNG development has not had an immediate negative effect on fish assemblages. Species richness, IBI scores and individual IBI metrics were similar between treatment and control sites even after applying a finite population correction factor, suggesting that there was no major influence of CBNG development on these fish assemblages. Additionally, there was not a strong relationship between IBI scores and the number or density of CBNG wells in the drainage area.

Fish were living in treatment streams that were composed largely or entirely of CBNG product water. Furthermore, recruitment of some species appears to be occurring in treatment streams. Although I did not sample larval fish, recruitment of fathead minnows and sand shiners appears to be occurring in Beaver Creek, a stream with direct discharges of CBNG product water. Adult male fathead minnows with spawning tubercles were observed in Beaver Creek at site C, 12.3 km upstream of the confluence with the Powder River. The long distance from the Powder River, the distribution of size classes, and the preference of small stream habitat (Brown 1971) of fathead minnows suggests that recruitment is occurring instream. Furthermore, fathead minnow are not a common species in the Powder River (B. Stewart, Wyoming Game and Fish, personal communication), and so are likely not migrants from the Powder River. Longnose dace and sand shiners survived and grew in sentinel cages at treatment sites where no or few fish were captured during fish surveys. Although fish appeared to have negative growth in the treatment cages on lower Squirrel Creek, the 30% of fish that died may have been larger fish, which would result in an apparent negative growth. Fish survival and growth in sentinel cages placed in fishless reaches suggests that factors such as a lack of instream connectivity rather than instream water quality limited fish distribution.

Reductions in IBI scores from 1994 to 2006 occurred at both historical treatment and historical control sites. This suggests that the reductions in 2006 IBI scores were not due to CBNG development but were associated with a factor that affected both treatment and control sites. Although Patton (1997) does not give detailed habitat information for the sites he sampled, it is possible that the reduction of biotic integrity scores throughout the basin may be related to drier conditions in 2006 relative to 1994. The mean monthly discharge in the Tongue River at State Line near Decker, Montana, in May 1994 was 35.7 m^3/s (1,261 cfs), but was only 14.1 m^3/s (498 cfs) in May 2006 (USGS 2007). The three years preceding the 1994 sampling events (i.e., 1991, 1992, and 1993) had 30% greater average annual discharges than the three years preceding the 2006 sampling events (USGS 2007). Greater stream discharge may have attracted more fish further upstream in the drainages and may have provided for better conditions for spawning, rearing, and survival of fish.

Although short term effects of CBNG development on fish assemblages are not alarming, some evidence suggests that CBNG may negatively affect fish assemblages over time. Index of biotic integrity scores and species richness were on average higher in control sites than treatment sites. Whereas these differences were not statistically significant, they may be a precursor to a biologically significant trend. Individual IBI metrics may be more sensitive to different aspects of environmental change than the overall IBI score. Three of four metrics that had negative relationships with the amount of CBNG development were related to species richness as opposed to trophic or reproductive function metrics. Species richness metrics may be more immediately sensitive to changes in water quality and quantity than trophic or reproductive function metrics, which may respond more slowly to changes in fish and invertebrate assemblages or habitat changes that result in the loss of spawning substrates (Karr and Yoder 2004). One of the species richness metrics, the number of species with long-lived individuals, is related to the permanence of suitable habitat and the absence of catastrophic disturbances (Bramblett et al. 2005). Variability in product-water management and water quality in treatment streams may limit the permanence of suitable habitat for some species to carry out their full life cycle.

Significant negative regressions between IBI metrics and the amount of CBNG development relationships may have been caused by two influential data points (Figure 13). The two sample sites with the largest number of CBNG wells in the drainage, Horse and Wildhorse creeks, had the largest watersheds, and also had the lowest scores for the number of native species, number of catostomid and ictalurid species, and number of species with long-lived individuals metrics. Species richness metrics are adjusted for watershed area to account for the expected positive correlation of species richness and watershed area (Karr 1981; Fausch et al. 1984; Bramblett et al. 2005). Therefore, a larger watershed must have more species present to score as well as a smaller watershed with fewer species. However, Horse and Wildhorse creeks did not have more fish species or more water volume or discharge than streams with smaller watershed areas. I do not know why these two streams have less water than smaller streams and if this is related to CBNG development.

Biotic integrity had a negative relationship with conductivity. Discharges from oil and gas development, irrigation, drought, and impoundments are all potential sources of increased conductivity (Williams 2001). Mean conductivity was on average more than 800 µmhos/cm greater in treatment streams than control streams, although conductivity in some control streams exceeded that in some treatment streams and variability likely precluded significant differences between treatment and control streams. If CBNG development increases conductivity it may affect the ability of species to persist over long periods, leading to decreases in biodiversity and overall biotic integrity. Biodiversity typically decreases in salinized rivers and streams as taxa sensitive to high salinity are extirpated and only 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).

Bicarbonate, one of the primary salts in CBNG product water, appears to be harmful to some species of fish. Although bicarbonate did not have a strong negative relationship with IBI scores, it was the only water quality variable to have a nearly significant negative relationship with the abundance of longnose dace. Longnose dace had a higher percent of occurrence in control streams than treatment streams and did not occur in sites with bicarbonate levels greater than 760 mg/L. Longnose dace are probably more sensitive to salts than other species in the study area (Rawson and Moore 1944). Laboratory and instream survival of 2-d old fathead minnows is reduced at concentrations of bicarbonate greater than 400 mg/L (Skaar et al. 2006; Farag et al. 2007). In three PRB streams receiving CBNG product water (Beaver and SA creeks, and Burger Draw), average instream 96-h survival of 2-d old fathead minnows in average concentrations of 1,245-2,315 mg/L bicarbonate was 30% compared to 78% in reference sites (Farag et al. 2007). However, I observed that recruitment of fathead minnows likely occurred in Beaver Creek where I measured bicarbonate concentrations of 1,940 mg/L. The disparity between my observations of recruitment in Beaver Creek and the low *in-situ* survival of larval fish could have been caused by a lack of acclimation or timing of the studies. Larval fish placed in CBNG product water were subjected to greater increases in conductivity and bicarbonate levels than fish placed in reference sites. Whereas the response of laboratory-reared larval fish to bicarbonate may be similar to instream larval fish response during the initial input of CBNG product water to a stream, older fish or future year classes of fish may acclimate to elevated salinity and have higher survival than unacclimated fish. However, the upper level acclimation is not known. Furthermore, hatching may normally occur at higher flows earlier in the spring when CBNG product water may be more diluted.

Native and non-native fish were captured in both treatment and control streams, but one non-native species, northern plains killifish, was observed almost exclusively in treatment streams. The closely related plains killifish was observed to persist in warmer temperatures, lower dissolved oxygen levels, and higher salinity than three cyprinid species in Texas streams (Ostrand and Wilde 2004). Such tolerances may give northern plains killifish a competitive advantage over native species in salinized waters (Douglas et al. 1994).

Four native species were observed exclusively in control streams. However, three of the four species were only captured in the East Fork Little Powder River, which was larger and probably more perennial than all other streams. Plains minnow were also observed exclusively in control streams, but only in one sample and in low abundances. Plains minnows have been declining basin-wide in Wyoming since the 1960’s (Patton 1997). The absence of plains minnows in treatment streams may be due to rarity rather than CBNG development.

Fewer species of fish were found within or below CBNG development than upstream of development in three streams. However, the unusual patterns were likely caused by altered flow regimes in all three streams due to irrigation, beaver dams, or stock ponds. Lower sites had less water than upstream sites. For example, the lowest site on Crazy Woman Creek was completely dewatered from irrigation withdrawals when water was flowing at the uppermost site. Beaver dams along Youngs Creek and a stock pond on Squirrel Creek altered natural flow regimes. It is unlikely that the reduced stream flows are related to CBNG development because coal seam aquifers in the PRB are largely confined aquifers that are bounded above and below by impermeable beds (Zelt et al. 1999). No reduction in natural spring inputs from coal seam aquifers has been observed in ground water monitoring networks in the PRB (Wheaton et al. 2007). Altered flow regimes confounded my ability to make valid comparisons of longitudinal patterns of species richness.

Study Limitations

My study was the largest and most comprehensive examination of the effects of CBNG on fish assemblages to date. Compared to previous studies in the Black Warrior Basin and the PRB, I surveyed more streams and used several different approaches. The use of fish as biological indicators has been a successful tool for biomonitoring networks and is a more holistic approach than exclusively monitoring water quality. However, several circumstances beyond my control created some study limitations.

Pre-development data was not available for the majority of study streams and prevented assessment of changes in fish assemblages following CBNG development. My comparison of treatment and control streams was confounded with drainage basin because all tributary streams of the Tongue and Powder rivers were developed, and undeveloped tributaries only existed in the Little Powder River basin. I expected treatment streams receiving CBNG product water to be deeper with greater discharge than control streams. However, treatment streams were not on average deeper and did not have greater discharge than control streams despite having larger watershed areas and input of CBNG product water. These unexpected patterns may be explained by differences in underlying aquifers. Seven of eight control streams were located in the Fox Hills Sandstone geologic formation (Vuke et al. 2007) where surface waters are influenced by the Fox Hills-Lower Hell Creek aquifer (Zelt et al. 1999). This aquifer is a reliable source of water for artesian wells, which may flow as much as 76 L/min along the major river valleys (Zelt et al. 1999). In contrast, all treatment streams were located in the Fort Union geologic formation where surface waters are influenced by the Wasatch-Tongue River aquifer, which typically has lower yields and is not known to be a significant source for artesian wells and surface flows (Zelt et al. 1999).

Variability in quality and amount of water produced and rapidly evolving water disposal methods complicate quantifying product water in a manner useful for assessing the effects to aquatic biota. The WYPDES discharge permit database was not readily available to the public, did not directly identify the fate of the product water (discharge to on-channel reservoir, off-channel reservoir, or stream), and lacked real-time product-water quality or quantity information. Because of database limitations, I was unable to assess the quantity and quality of CBNG product water being discharged to streams at any given time. The number of CBNG wells and the type of product-water management in the drainage were the best variables available to determine the relative effects of product water on fish assemblages, but these are not accurate measures of product-water quantity or water quality. Additionally, product-water variability may have contributed to the variability in response variables and led to non-significant results.

This study was conducted during two years with below normal rainfall and followed several years of below normal precipitation and above normal summer temperatures. Extended drought and warm temperatures probably resulted in lower IBI scores for all streams than would be expected in normal precipitation years. The fish assemblages in streams during the study may represent the most tolerant fish that persisted through several years of harsh conditions. Therefore, differences between treatment and control streams could be more pronounced following years of adequate precipitation.

Effluent discharges may increase habitat for fish provided water quality is adequate (Brooks et al. 2006). Similarly, the addition of product water in the PRB may increase water yield to that comparable to a stream with a larger watershed area. If water quality of product water is adequate, this may artificially inflate IBI scores because species richness metrics in the IBI are adjusted to watershed area.

Management Implications

Potential for coalbed natural gas development exists in over 20 countries (Talkington 2002) and active exploration or production of CBNG is occurring in the United States, Canada, western Europe, Japan, Australia, and New Zealand (Talkington 2002; Johnson 2004). Water quality monitoring has traditionally focused on the presence of chemical contaminants rather than aquatic biota (Karr 2006), but water quality laws and guidelines are shifting focus to incorporate the biology of waters in many countries (Karr 2006). As the focus on biological organisms intensifies and CBNG development expands, the demand for effective biological monitoring will increase. The approaches I used in my study were largely effective to determine the short term effects of CBNG on fish assemblages in the PRB. However, the inferences that can be made among geologic basins with CBNG development are limited because the major ion composition of product water and the local fish assemblages vary among basins. Therefore, I recommend the use of my study design along with the following recommendations as a framework for evaluating the effects of CBNG development in other basins.

Surveys of aquatic biota should be conducted before the development and production of CBNG and monitoring of fish assemblages should continue through the life of development and reclamation. Direct biological monitoring will provide a mechanism to directly assess the condition of aquatic resources, diagnose causes of degradation, define conservation actions, and evaluate the effectiveness of management decisions (Karr 2006). Fish assemblage response to CBNG in small tributary streams may also help predict the effects of CBNG development on fish assemblages in the larger streams and rivers. Because tributary streams are smaller, less stable, and have less dilution capacity, they would likely respond to anthropogenic stressors sooner than larger streams.

Research efforts on the toxicity of bicarbonate on aquatic biota should continue until a water quality standard is developed. Numeric water quality standards guarantee some protection for multiple aquatic species and are reasonably easy to implement and enforce from a regulatory standpoint. Water quantity is likely a limiting factor controlling prairie stream fish assemblages and CBNG product water may provide a supplemental water resource for fish during dry conditions, but it must meet minimum quality requirements.

Research should be conducted to assess fish assemblage response to continuous input of product water in normally stochastic systems. The natural stochasticity of the Great Plains ecosystem likely makes these streams more dynamic and their biota less vulnerable to changes in water quality and quantity. However, replacement of stochastic flows with more regular flows will likely result in changes in the fish assemblage. Non-native fish may have a competitive advantage in these situations. Seasonal change in water temperature is an important environmental cue for the movement and spawning behavior of many fish species (Gale 1986; Bjornn and Resier 1991). Intermittent streams provide an ideal nursery environment for white suckers and creek chubs because they warm earlier than perennial streams allowing for a longer growing season for age-0 fish, and the lack of discharge excludes large predators (Williams and Coad 1979). Therefore it is critical that biological dynamics in naturally intermittent streams systems are understood and considered in future management decisions (Brooks et al. 2006).

Discharge permits should have additional monitoring requirements to facilitate the accurate assessment of the effect of product-water inputs. Product-water discharge points and streams receiving product water should be equipped with remote stations to collect continuous discharge, water quality, and water temperature information. Permits should also include a field that easily identifies the fate of the product water. This information should be housed in a publicly accessible web based database that is regularly updated or linked to real-time data similar to many existing stream monitoring networks. This information will be especially important in future evaluations of the long term changes in water quality, fish assemblages, and lack of seasonality created by the constant input of CBNG product water.

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APPENDICES

APPENDIX A

FISH SURVEY RESULTS FROM TREATMENT AND CONTROL STREAMS

APPENDIX A. Species collected at treatment and control sites during summers of 2005 and 2006. (* = dry site)

	Beaver Creek			Cottonwood Creek						Dry Creek (Little Powder)					
	A	B	C	A		B		C		A		B		C	
	2006	2006	2006	2005	2006	2005	2006	2005	2006	2005	2006	2005	2006	2005	2006
Family															
Common name, *Genus species*															
Cyprinidae															
lake chub, *Couesius plumbeus*	0	0	0	0	*	0	0	0	0	0	0	0	0	0	0
common carp, *Cyprinus carpio*	0	0	0	0	*	0	0	0	0	0	0	0	0	0	0
brassy minnow, *Hybognathus hankinsoni*	0	0	0	0	*	0	0	0	0	0	0	0	0	0	0
plains minnow, *Hybognathus placitus*	0	0	0	5	*	0	0	0	0	0	0	0	0	0	0
sand shiner, *Notropis stramineus*	207	35	120	73	*	0	0	0	0	4	3	44	16	54	14
fathead minnow, *Pimephales promelas*	582	392	148	24	*	0	20	4	15	3	0	0	1	0	7
flathead chub, *Platygobio gracilis*	0	0	0	9	*	0	0	0	0	0	0	0	0	0	0
longnose dace, *Rhinichthys cataractae*	0	0	0	1	*	0	0	0	0	143	24	13	32	51	28
creek chub, *Semotilus atromaculatus*	0	0	0	0	*	0	0	0	0	0	0	0	0	0	0
Catostomidae															
river carpsucker, *Carpoides carpio*	0	0	0	0	*	0	0	0	0	0	0	0	0	0	0
longnose sucker, *Catostomus catostomus*	0	0	0	0	*	0	0	0	0	0	0	0	0	0	0
white sucker, *Catostomus commersonii*	4	0	1	0	*	0	0	0	0	7	3	5	2	3	1
mountain sucker, *Catostomus platyrhynchus*	0	0	0	0	*	0	0	0	0	0	0	0	0	0	0
shorthead redhorse, *Moxostoma macrolepidotum*	0	0	0	0	*	0	0	0	0	0	0	0	0	0	0
Ictaluridae															
black bullhead, *Ameiurus melas*	3	7	0	0	*	0	0	0	0	0	1	6	2	0	0
yellow bullhead, *Ameiurus natalis*	0	0	0	0	*	0	0	0	0	0	0	0	0	0	0
channel catfish, *Ictalurus punctatus*	0	0	0	0	*	0	0	0	0	0	0	0	0	0	0
stonecat, *Noturus flavus*	0	0	0	0	*	0	0	0	0	0	0	0	0	0	0
Cyprinodontidae															
Northern plains killifish, *Fundulus kansae*	0	227	108	0	*	0	0	0	0	0	0	0	0	0	0
Centrarchidae															
green sunfish, *Lepomis cyanellus*	0	1	0	0	*	0	0	0	0	0	0	3	1	0	0

APPENDIX A.—Extended.

	East Fork Little Powder River						Horse Creek		Middle Prong Wildhorse Creek					
	A		B		C		A		A		B		C	
Family	2005	2006	2005	2006	2005	2006	2005	2006	2005	2006	2005	2006	2005	2006
Common name, *Genus species*														
Cyprinidae														
lake chub, *Couesius plumbeus*	0	0	0	0	0	0	0	0	0	0	0	0	0	0
common carp, *Cyprinus carpio*	2	0	0	0	0	0	0	0	2	5	0	0	0	0
brassy minnow, *Hybognathus hankinsoni*	0	0	0	0	0	0	0	0	108	11	0	0	0	0
plains minnow, *Hybognathus placitus*	0	0	0	0	0	0	0	0	0	0	0	0	0	0
sand shiner, *Notropis stramineus*	9	11	3	8	0	0	0	0	101	74	0	0	0	0
fathead minnow, *Pimephales promelas*	4	2	0	0	0	1	871	1105	618	34	0	0	0	0
flathead chub, *Platygobio gracilis*	10	9	2	3	0	0	0	0	0	0	0	0	0	0
longnose dace, *Rhinichthys cataractae*	0	0	11	2	10	10	0	0	0	0	0	0	0	0
creek chub, *Semotilus atromaculatus*	0	0	0	0	4	0	0	0	44	60	0	0	0	0
Catostomidae														
river carpsucker, *Carpoides carpio*	0	0	0	0	0	0	0	0	0	0	0	0	0	0
longnose sucker, *Catostomus catostomus*	0	0	2	0	0	0	0	0	0	0	0	0	0	0
white sucker, *Catostomus commersonii*	5	0	1	2	1	1	0	0	209	103	0	0	0	0
mountain sucker, *Catostomus platyrhynchus*	0	0	0	0	0	0	0	0	0	0	0	0	0	0
shorthead redhorse, *Moxostoma macrolepidotum*	1	0	0	0	0	0	0	0	0	0	0	0	0	0
Ictaluridae														
black bullhead, *Ameiurus melas*	0	0	1	2	5	1	0	0	1	104	0	0	0	0
yellow bullhead, *Ameiurus natalis*	0	0	0	0	0	0	0	0	0	0	0	0	0	0
channel catfish, *Ictalurus punctatus*	2	4	4	0	0	0	0	0	0	0	0	0	0	0
stonecat, *Noturus flavus*	1	3	3	3	4	3	0	0	0	0	0	0	0	0
Cyprinodontidae														
Northern plains killifish, *Fundulus kansae*	0	0	0	0	0	0	0	0	0	2	0	0	0	0
Centrarchidae														
green sunfish, *Lepomis cyanellus*	11	1	1	0	0	0	0	23	216	197	0	0	0	0

APPENDIX A.—Extended.

Family	Mitchell Creek						Olmstead Creek		Ranch Creek					
	A		B		C		A		A		B		C	
	2005	2006	2005	2006	2005	2006	2005	2006	2005	2006	2005	2006	2005	2006
Common name, *Genus species*														
Cyprinidae														
lake chub, *Couesius plumbeus*	0	0	0	0	0	0	0	0	0	0	0	0	0	0
common carp, *Cyprinus carpio*	0	0	0	0	0	0	0	0	0	0	0	0	0	0
brassy minnow, *Hybognathus hankinsoni*	0	0	0	0	0	0	0	0	0	0	15	47	6	32
plains minnow, *Hybognathus placitus*	0	0	0	0	0	0	0	0	0	0	0	0	0	0
sand shiner, *Notropis stramineus*	0	0	0	0	0	0	0	0	6	0	5	0	4	0
fathead minnow, *Pimephales promelas*	4	1	15	4	0	7	0	0	7	0	0	3	34	20
flathead chub, *Platygobio gracilis*	0	0	0	0	0	0	0	0	0	0	0	0	0	0
longnose dace, *Rhinichthys cataractae*	0	0	0	0	0	0	0	0	2	8	0	4	0	0
creek chub, *Semotilus atromaculatus*	0	0	0	0	0	0	0	0	14	1	5	16	0	170
Catostomidae														
river carpsucker, *Carpoides carpio*	0	0	0	0	0	0	0	0	0	0	0	0	0	0
longnose sucker, *Catostomus catostomus*	0	0	0	0	0	0	0	0	0	0	0	0	0	0
white sucker, *Catostomus commersonii*	0	0	0	0	0	0	11	0	0	0	0	0	0	0
mountain sucker, *Catostomus platyrhynchus*	0	0	0	0	0	0	0	0	0	0	0	0	0	0
shorthead redhorse, *Moxostoma macrolepidotum*	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Ictaluridae														
black bullhead, *Ameiurus melas*	0	0	0	0	0	0	0	0	0	0	0	0	0	0
yellow bullhead, *Ameiurus natalis*	0	0	0	0	0	0	0	0	0	0	0	0	0	0
channel catfish, *Ictalurus punctatus*	0	0	0	0	0	0	0	0	0	0	0	0	0	0
stonecat, *Noturus flavus*	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Cyprinodontidae														
Northern plains killifish, *Fundulus kansae*	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Centrarchidae														
green sunfish, *Lepomis cyanellus*	2	1	0	0	0	0	1	0	2	1	0	1	3	19

APPENDIX A.—Extended.

	Spring Creek					Squirrel Creek					
	A		B	C		A		B		C	
Family	2005	2006	2005	2005	2006	2005	2006	2005	2006	2005	2006
Common name, *Genus species*											
Cyprinidae											
lake chub, *Couesius plumbeus*	0	0	0	0	0	0	0	0	0	0	12
common carp, *Cyprinus carpio*	0	1	0	0	0	1	0	0	0	0	0
brassy minnow, *Hybognathus hankinsoni*	0	0	0	0	0	0	0	7	43	13	0
plains minnow, *Hybognathus placitus*	0	0	0	0	0	0	0	0	0	0	0
sand shiner, *Notropis stramineus*	9	2	0	0	0	0	0	0	0	0	0
fathead minnow, *Pimephales promelas*	26	41	0	11	24	0	0	51	518	184	14
flathead chub, *Platygobio gracilis*	0	0	0	0	0	0	0	0	0	0	0
longnose dace, *Rhinichthys cataractae*	0	0	0	0	0	0	0	0	0	16	3
creek chub, *Semotilus atromaculatus*	0	0	0	0	0	0	0	0	1	11	0
Catostomidae											
river carpsucker, *Carpoides carpio*	0	0	0	0	0	0	0	0	0	0	0
longnose sucker, *Catostomus catostomus*	0	0	0	0	0	0	0	0	0	0	0
white sucker, *Catostomus commersonii*	0	0	0	0	0	0	1	0	1	0	0
mountain sucker, *Catostomus platyrhynchus*	0	0	0	0	0	0	0	0	0	0	0
shorthead redhorse, *Moxostoma macrolepidotum*	0	0	0	0	0	0	0	0	0	0	0
Ictaluridae											
black bullhead, *Ameiurus melas*	15	9	0	0	0	0	0	0	0	0	0
yellow bullhead, *Ameiurus natalis*	0	0	0	0	0	0	0	0	0	0	0
channel catfish, *Ictalurus punctatus*	0	0	0	0	0	0	0	0	0	0	0
stonecat, *Noturus flavus*	0	0	0	0	0	0	0	0	0	0	0
Cyprinodontidae											
Northern plains killifish, *Fundulus kansae*	0	0	0	0	0	0	0	0	0	0	0
Centrarchidae											
green sunfish, *Lepomis cyanellus*	4	0	0	0	0	0	0	0	0	0	0

APPENDIX A.—Extended.

	Trail Creek				Wildcat Creek		Wildhorse Creek	
	A		B		A		A	
Family	2005	2006	2005	2006	2005	2006	2005	2006
Common name, *Genus species*								
Cyprinidae								
lake chub, *Couesius plumbeus*	0	*	0	*	0	99	0	*
common carp, *Cyprinus carpio*	0	*	0	*	0	0	0	*
brassy minnow, *Hybognathus hankinsoni*	0	*	0	*	0	0	0	*
plains minnow, *Hybognathus placitus*	0	*	0	*	0	0	0	*
sand shiner, *Notropis stramineus*	0	*	0	*	0	0	0	*
fathead minnow, *Pimephales promelas*	2	*	0	*	7	103	3	*
flathead chub, *Platygobio gracilis*	0	*	0	*	0	0	0	*
longnose dace, *Rhinichthys cataractae*	0	*	0	*	0	0	0	*
creek chub, *Semotilus atromaculatus*	3	*	0	*	0	0	6	*
Catostomidae								
river carpsucker, *Carpoides carpio*	0	*	0	*	0	0	0	*
longnose sucker, *Catostomus catostomus*	0	*	0	*	0	0	0	*
white sucker, *Catostomus commersonii*	0	*	0	*	0	4	0	*
mountain sucker, *Catostomus platyrhynchus*	0	*	0	*	0	0	0	*
shorthead redhorse, *Moxostoma macrolepidotum*	0	*	0	*	0	0	0	*
Ictaluridae								
black bullhead, *Ameiurus melas*	0	*	0	*	0	0	0	*
yellow bullhead, *Ameiurus natalis*	0	*	0	*	0	0	0	*
channel catfish, *Ictalurus punctatus*	0	*	0	*	0	0	0	*
stonecat, *Noturus flavus*	0	*	0	*	0	0	0	*
Cyprinodontidae								
Northern plains killifish, *Fundulus kansae*	0	*	0	*	0	0	9	*
Centrarchidae								
green sunfish, *Lepomis cyanellus*	6	*	0	*	0	0	2	*

APPENDIX B

WATER QUALITY RESULTS FROM TREATMENT AND CONTROL STREAMS

APPENDIX B.—Field and laboratory water quality results for treatment (T) and control (C) streams.

	Beaver Creek			Cottonwood Creek						Dry Creek (Little Powder)			
	A	B	C	A		B		C		A		B	
	2006	2006	2006	2005	2006	2005	2006	2005	2006	2005	2006	2005	2006
Field values													
Conductivity (umhos/cm)	2942	2676	2601	2518	*	4003	4195	1649	1731	2761	3245	2892	3239
Dissolved oxygen (mg/L)	6.92	6.02	9.55	4.56	*	0.7	2.05	**	2.31	7.64	9.35	9.67	8.75
Temperature (°C)	18.1	27	25.8	21.4	*	17.6	23.8	26.2	18.6	20.2	23.7	26	21.8
pH	9.2	9.5	9.1	8.2	*	8.1	8.5	9.2	8.8	8.3	8.7	8.8	8.6
Turbidity (NTU)	33	256	10	71	*	38	150	7	17	**	4	**	3
Lab values													
pH	**	**	**	8	*	x	8	x	x	9	8	x	8
Conductivity (umhos/cm)	**	**	**	3200	*	x	965	x	x	3130	3440	x	3460
Total dissolved solids (mg/L)	**	**	**	2250	*	x	763	x	x	2710	2820	x	2770
Alkalinity (mg/L)	**	1409	1406	604	*	x	196	x	x	180	137	x	141
Chloride (mg/L)	**	15	15	19	*	x	7	x	x	178	205	x	214
Sulfate (mg/L)	**	1	25	1060	*	x	251	x	x	1450	1370	x	1470
Bicarbonate (mg/L)	**	**	**	731	*	x	240	x	x	217	168	x	172
Ammonia (mg/L)	**	2	1	0	*	x	0	x	x	0	0	x	0
Calcium (mg/L)	**	26	13	57	*	x	41	x	x	398	384	x	392
Magnesium (mg/L)	**	18	18	59	*	x	18	x	x	115	111	x	112
Potassium (mg/L)	**	16	14	11	*	x	9	x	x	88	86	x	87
Sodium (mg/L)	**	565	584	638	*	x	120	x	x	181	204	x	207

* dry site
** sampling error
X no sample

APPENDIX B.—Extended

	Dry Creek		East Fork Little Powder						Horse Creek	
	C		A		B		C		A	
	2005	2006	2005	2006	2005	2006	2005	2006	2005	2006
Field values										
Conductivity (umhos/cm)	2855	3132	1702	1673	1520	1519	1400	1458	4258	2267
Dissolved oxygen (mg/L)	6.64	8.52	5.86	6.29	6.2	6.89	4.62	10.18	10.89	9.06
Temperature (°C)	23.8	21	24.9	19.5	27.6	19.9	21.7	22.7	24.3	27.2
pH	8.2	8.5	8.9	8.8	8.9	8.8	8.7	8.8	9.5	9.9
Turbidity (NTU)	2	5	236	85	80	50	127	38	10	7
Lab values										
pH	x	8	9	9	x	9	x	9	x	9
Conductivity (umhos/cm)	x	3200	1690	1870	x	1600	x	1460	x	3560
Total dissolved solids (mg/L)	x	2610	1150	1250	x	1060	x	990	x	2770
Alkalinity (mg/L)	x	113	432	416	x	399	x	395	x	466
Chloride (mg/L)	x	199	5	6	x	4	x	4	x	11
Sulfate (mg/L)	x	1360	466	515	x	388	x	335	x	1620
Bicarbonate (mg/L)	x	138	494	453	x	453	x	452	x	489
Ammonia (mg/L)	x	0	0	0	x	0	x	0	x	0
Calcium (mg/L)	x	387	22	20	x	19	x	18	x	103
Magnesium (mg/L)	x	101	10	10	x	6	x	6	x	180
Potassium (mg/L)	x	90	2	4	x	2	x	2	x	30
Sodium (mg/L)	x	177	372	389	x	326	x	286	x	518

* dry site
** sampling error
X no sample

APPENDIX B.—Extended

	Mid Prong Wildhorse Creek						Mitchell Creek					
	A		B		C		A		B		C	
	2005	2006	2005	2006	2005	2006	2005	2006	2005	2006	2005	2006
Field values												
Conductivity (umhos/cm)	**	4890	**	*	2201	2332	3185	2750	6290	3706	7010	7400
Dissolved oxygen (mg/L)	**	9.51	**	*	2.48	5.49	3.06	3.95	8.71	3.8	6.2	2.13
Temperature (°C)	**	29.2	**	*	19.5	30.2	25.2	19.7	22.7	26.8	20.1	18.4
pH	8.3	8.8	8.8	*	8.3	8.5	8.4	8.5	8.2	8.3	8.9	8.3
Turbidity (NTU)	33	45	41	*	8	133	5	7	**	6	**	20
Lab values												
pH	8	8	x	*	x	8	8	8	x	8	x	8
Conductivity (umhos/cm)	8100	8600	x	*	x	2340	1020	1340	x	3000	x	2720
Total dissolved solids (mg/L)	7920	7570	x	*	x	1450	723	928	x	2220	x	2000
Alkalinity (mg/L)	414	474	x	*	x	1320	249	186	x	345	x	251
Chloride (mg/L)	25	33	x	*	x	8	9	13	x	25	x	25
Sulfate (mg/L)	4760	5100	x	*	x	6	241	426	x	1240	x	1030
Bicarbonate (mg/L)	501	540	x	*	x	1490	304	227	x	421	x	306
Ammonia (mg/L)	0	0	x	*	x	1	0	0	x	0	x	0
Calcium (mg/L)	320	249	x	*	x	19	41	70	x	119	x	104
Magnesium (mg/L)	416	421	x	*	x	12	27	34	x	73	x	65
Potassium (mg/L)	23	36	x	*	x	9	15	12	x	16	x	15
Sodium (mg/L)	1320	1490	x	*	x	569	136	156	x	446	x	411

* dry site
** sampling error
X no sample

APPENDIX B.—Extended

	Olmstead Creek		Ranch Creek						SA Creek			
	A		A		B		C		A		B	
	2005	2006	2005	2006	2005	2006	2005	2006	2005	2006	2005	2006
Field values												
Conductivity (umhos/cm)	7360	7050	2125	2312	1404	1419	1134	1182	4924	7190	5540	*
Dissolved oxygen (mg/L)	5.66	13.86	7.02	6.34	9.22	6.02	5.69	5.22	5.85	5.65	8.72	*
Temperature (°C)	24.1	25.7	11.9	22.2	20.2	18.2	21	23.8	18.8	17.1	27.9	*
pH	8.8	8.3	8.3	8.4	8.5	8.3	8.3	8.3	8.3	8.3	8.5	*
Turbidity (NTU)	6	8	7	20	7	8	2	4	9	7	7	*
Lab values												
pH	9	8	9	8	x	8	x	8	8	8	x	*
Conductivity (umhos/cm)	7810	7780	3150	4040	x	1560	x	1270	8060	8570	x	*
Total dissolved solids (mg/L)	4820	4600	2280	3010	x	1020	x	807	7090	7900	x	*
Alkalinity (mg/L)	257	281	399	413	x	300	x	387	402	398	x	*
Chloride (mg/L)	1840	1830	19	26	x	13	x	7	40	47	x	*
Sulfate (mg/L)	941	959	1190	1730	x	432	x	227	4860	4610	x	*
Bicarbonate (mg/L)	298	343	450	475	x	358	x	472	490	475	x	*
Ammonia (mg/L)	0	0	0	0	x	0	x	0	0	0	x	*
Calcium (mg/L)	108	138	71	112	x	52	x	40	222	256	x	*
Magnesium (mg/L)	91	79	37	52	x	19	x	17	465	460	x	*
Potassium (mg/L)	53	59	4	7	x	3	x	4	42	38	x	*
Sodium (mg/L)	1450	1420	630	745	x	251	x	217	1440	1370	x	*

* dry site
** sampling error
X no sample

APPENDIX B.—Extended

	SA Creek		Spotted Horse Creek						Spring Creek				
	C		A		B		C		A		B	C	
	2005	2006	2005	2006	2005	2006	2005	2006	2005	2006	2005	2005	2006
Field values													
Conductivity (umhos/cm)	4402	2797	**	6100	4448	9090	4920	8250	6230	6390	2850	1919	3237
Dissolved oxygen (mg/L)	7.82	7.95	**	2.1	10.8	9.5	3.78	7.8	3.54	1.96	16.1	10.9	15.29
Temperature (°C)	26.6	24.5	**	13.7	24.3	27.1	21.8	17.5	16.3	21.9	20	27.5	27.7
pH	8.5	8.8	9	8.2	8.5	8.5	8.1	8.1	8.1	8.3	8.8	9.6	10.5
Turbidity (NTU)	15	65	75	70	8	3	5	3	13	40	**	**	12
Lab values													
pH	x	9	*	*	*	*	*	*	8	8	x	x	7
Conductivity (umhos/cm)	x	3230	*	*	*	*	*	*	5710	7990	x	x	663
Total dissolved solids (mg/L)	x	2190	*	*	*	*	*	*	3710	5170	x	x	509
Alkalinity (mg/L)	x	1090	*	*	*	*	*	*	363	296	x	x	292
Chloride (mg/L)	x	18	*	*	*	*	*	*	1090	1600	x	x	8
Sulfate (mg/L)	x	603	*	*	*	*	*	*	974	1150	x	x	33
Bicarbonate (mg/L)	x	1180	*	*	*	*	*	*	443	361	x	x	356
Ammonia (mg/L)	x	0	0	0	0	0	0	0	0	0	x	x	0
Calcium (mg/L)	x	34	*	*	*	*	*	*	215	341	x	x	24
Magnesium (mg/L)	x	78	*	*	*	*	*	*	59	69	x	x	16
Potassium (mg/L)	x	14	*	*	*	*	*	*	83	124	x	x	22
Sodium (mg/L)	x	661	*	*	*	*	*	*	977	1180	x	x	97

* dry site
** sampling error
X no sample

APPENDIX B.—Extended

	Squirrel Creek						Trail Creek			
	A		B		C		A		B	
	2005	2006	2005	2006	2005	2006	2005	2006	2005	2006
Field values										
Conductivity (umhos/cm)	5760	6030	3591	2963	1430	1453	2437	*	1637	*
Dissolved oxygen (mg/L)	4.42	2.78	11.6	12.54	7.8	5.62	5.21	*	2.8	*
Temperature (°C)	15.7	17	29.7	26	17.5	24	20.5	*	26	*
pH	7.8	8.3	9.1	8.6	8.5	8.7	8.7	*	8.9	*
Turbidity (NTU)	4	6	5	8	2	15	7	*	4	*
Lab values										
pH	8	8	8	8	8	8	*	*	x	*
Conductivity (umhos/cm)	5890	6150	3370	3160	1460	1530	*	*	x	*
Total dissolved solids (mg/L)	5780	5590	2850	2430	1040	1030	*	*	x	*
Alkalinity (mg/L)	600	514	771	649	512	493	*	*	x	*
Chloride (mg/L)	18	16	8	12	4	4	*	*	x	*
Sulfate (mg/L)	3400	3540	1410	1230	359	386	*	*	x	*
Bicarbonate (mg/L)	733	627	932	792	625	601	*	*	x	*
Ammonia (mg/L)	0	0	0	0	0	0	*	*	x	*
Calcium (mg/L)	271	220	133	114	95	92	*	*	x	*
Magnesium (mg/L)	546	525	272	251	123	125	*	*	x	*
Potassium (mg/L)	27	26	18	21	9	11	*	*	x	*
Sodium (mg/L)	656	662	316	316	69	76	*	*	x	*

* dry site
** sampling error
X no sample

APPENDIX B.—Extended

	Wildcat Creek		Wildhorse Creek	
	A		A	
	2005	2006	2005	2006
Field values				
Conductivity (umhos/cm)	5030	3255	**	*
Dissolved oxygen (mg/L)	5.82	3.71	**	*
Temperature (°C)	22.8	20.9	**	*
pH	8.3	8.3	8.5	*
Turbidity (NTU)	6	38	**	*
Lab values				
pH	8	*	8	*
Conductivity (umhos/cm)	1470	*	760	*
Total dissolved solids (mg/L)	1070	*	598	*
Alkalinity (mg/L)	197	*	396	*
Chloride (mg/L)	5	*	14	*
Sulfate (mg/L)	544	*	9	*
Bicarbonate (mg/L)	240	*	482	*
Ammonia (mg/L)	0	*	0	*
Calcium (mg/L)	70	*	12	*
Magnesium (mg/L)	63	*	6	*
Potassium (mg/L)	17	*	4	*
Sodium (mg/L)	167	*	165	*

* dry site
** sampling error
X no sample

APPENDIX C

FISH SURVEY RESULTS FROM PRODUCT WATER STREAMS

APPENDIX C.—Species collected at product water sites during summers of 2005 and 2006.

	Burger Draw			Dry Creek					
	A	B	C	A		B		C	
Family / Common name, *Genus species*	2005	2005	2005	2005	2006	2005	2006	2005	2006
Cyprinidae									
lake chub, *Couesius plumbeus*	0	0	0	0	0	0	0	0	0
common carp, *Cyprinus carpio*	0	0	0	0	0	0	0	0	0
brassy minnow, *Hybognathus hankinsoni*	0	0	0	0	0	0	0	0	0
plains minnow, *Hybognathus placitus*	0	0	0	0	0	0	0	0	0
sand shiner, *Notropis stramineus*	285	0	0	0	0	0	0	0	0
fathead minnow, *Pimephales promelas*	16	0	0	0	0	0	0	0	0
flathead chub, *Platygobio gracilis*	34	0	0	0	0	0	0	0	0
longnose dace, *Rhinichthys cataractae*	0	0	0	0	0	0	0	0	0
creek chub, *Semotilus atromaculatus*	0	0	0	0	0	0	0	0	0
Catostomidae									
river carpsucker, *Carpoides carpio*	5	0	0	0	0	0	0	0	0
longnose sucker, *Catostomus catostomus*	0	0	0	0	0	0	0	0	0
white sucker, *Catostomus commersonii*	0	0	0	0	0	0	0	0	0
mountain sucker, *Catostomus platyrhynchus*	0	0	0	0	0	0	0	0	0
shorthead redhorse, *Moxostoma macrolepidotum*	0	0	0	0	0	0	0	0	0
Ictaluridae									
black bullhead, *Ameiurus melas*	4	0	0	0	0	0	0	0	0
yellow bullhead, *Ameiurus natalis*	0	0	0	0	0	0	0	0	0
channel catfish, *Ictalurus punctatus*	0	0	0	0	0	0	0	0	0
stonecat, *Noturus flavus*	0	0	0	0	0	0	0	0	0
Cyprinodontidae									
northern plains killifish, *Fundulus kansae*	55	0	0	0	0	0	0	0	0
Centrarchidae									
green sunfish, *Lepomis cyanellus*	0	0	0	0	0	0	0	0	0

APPENDIX D

WATER QUALITY RESULTS FROM PRODUCT WATER STREAMS

APPENDIX D.—Field and laboratory water quality results for product water streams.

	Burger Draw			Dry Creek (Powder)					
	A	B	C	A		B		C	
	2005	2005	2005	2005	2006	2005	2006	2005	2006
Field values									
Conductivity (umhos/cm)	3700	3726	3933	3430	2278	3366	2350	3350	2542
Dissolved oxygen (mg/L)	3.2	4.93	5.36	7.47	7.52	7.68	6.85	6.32	6.02
Temperature (°C)	20.5	27.1	25.9	15.6	13.4	21.8	19.4	17.7	23.8
pH	8.8	8.9	9	9.1	8.3	9.2	8.3	9.2	8.3
Turbidity (NTU)	52	67	28	101	X	388	X	332	X
Lab values									
pH	9	9	**	9	9	**	9	**	9
Conductivity (umhos/cm)	3730	3780	**	3210	3660	**	3610	**	3650
Total dissolved solids (mg/L)	2470	2450	**	2160	2430	**	2420	**	2420
Alkalinity (mg/L)	2280	2240	**	1700	2000	**	1880	**	1900
Chloride (mg/L)	33	33	**	42	48	**	47	**	46
Sulfate (mg/L)	10	9	**	108	105	**	88	**	87
Bicarbonate (mg/L)	2380	2350	**	1680	1930	**	1650	**	1770
Ammonia (mg/L)	0	1	**		0	**	0	**	0
Calcium (mg/L)	18	19	**	12	14	**	11	**	12
Magnesium (mg/L)	30	30	**	18	16	**	15	**	15
Potassium (mg/L)	43	43	**	32	37	**	37	**	38
Sodium (mg/L)	975	1010	**	827	955	**	943	**	937

** sampling error
X no sample

APPENDIX E

FISH SURVEY RESULTS FROM LONGITUDINAL STREAMS

APPENDIX E.—Species collected at longitudinal sites during summer of 2006. (* = dry site)

Family	Crazy Woman Creek					Squirrel Creek					Youngs Creek				
	A	B	C	D	E	A	B	C	D	E	A	B	C	D	E
Common name, *Genus species*															
Hiodontidae															
goldeye, *Hiodon alosoides*	*	0	1	0	0	0	0	0	0	0	0	0	0	0	0
Cyprinidae															
lake chub, *Couesius plumbeus*	*	0	0	0	0	0	0	0	76	12	0	1	0	6	0
common carp, *Cyprinus carpio*	*	0	27	34	15	0	0	0	0	0	0	0	0	0	0
brassy minnow, *Hybognathus hankinsoni*	*	0	0	0	0	0	0	43	8	0	0	0	0	1	0
sand shiner, *Notropis stramineus*	*	75	633	498	216	0	0	0	0	0	0	0	0	0	0
fathead minnow, *Pimephales promelas*	*	0	4	0	0	0	0	518	112	14	0	2	46	17	4
flathead chub, *Platygobio gracilis*	*	12	10	18	6	0	0	0	0	0	0	0	0	0	0
longnose dace, *Rhinichthys cataractae*	*	443	64	54	10	0	0	0	6	3	2	3	1	135	0
creek chub, *Semotilus atromaculatus*	*	0	0	0	0	0	5	1	0	0	0	1	6	63	1
Catostomidae															
white sucker, *Catostomus commersonii*	*	161	434	93	8	1	0	1	0	0	0	2	10	33	0
mountain sucker, *Catostomus platyrhynchus*	*	0	0	2	0	0	0	0	0	0	0	0	0	3	0
shorthead redhorse, *Moxostoma macrolepidotum*	*	0	5	0	0	0	0	0	0	0	0	0	0	0	0
Ictaluridae															
black bullhead, *Ameiurus melas*	*	0	116	79	1	0	0	0	0	0	0	0	1	0	0
channel catfish, *Ictalurus punctatus*	*	0	2	1	0	0	0	0	0	0	0	0	0	0	0
stonecat, *Noturus flavus*	*	2	0	3	2	0	0	0	0	0	0	0	0	0	0
Centrarchidae															
smallmouth bass, *Micropterus dolomieu*	*	0	0	0	0	0	0	0	0	0	0	0	1	0	0
green sunfish, *Lepomis cyanellus*	*	0	0	1	15	0	0	0	0	0	0	0	0	0	0

APPENDIX F

WATER QUALITY RESULTS FROM LONGITUDINAL STREAMS

APPENDIX F.—Field and laboratory water quality results from 2006 for longitudinal streams.

	Crazy Woman Creek					Squirrel Creek					Youngs Creek				
	A	B	C	D	E	A	B	C	D	E	A	B	C	D	E
Field values															
Conductivity (umhos/cm)	*	3191	6650	2967	2807	6030	6920	2963	1435	1453	1038	988	1016	584	473
Dissolved oxygen (mg/L)	*	3.58	5.69	5	7.41	2.78	1.21	12.5	7.25	5.62	7.33	6.88	6.9	9.7	8.89
Temperature (°C)	*	21.6	22.5	20.3	25.7	17	21	26	23.9	24	20.7	19.3	16.2	20	12.4
pH	*	8.7	8.4	8.5	8.7	8.3	8.1	8.6	8.6	8.7	8.8	8.8	8.9	8.4	8.8
Turbidity (NTU)	*	63	34	11	30	6	33	8	12	15	47	44	51	20	7
Lab values															
pH	*	8	8	8	8	8	8	8	8	8	9	9	8	8	9
Conductivity (umhos/cm)	*	4100	8880	3240	4470	6150	9450	3160	1530	1530	974	1110	1140	609	490
Total dissolved solids (mg/L)	*	3800	8760	2840	4270	5590	9290	2430	1020	1030	622	716	745	357	284
Alkalinity (mg/L)	*	186	335	228	278	514	779	649	496	493	295	374	398	305	233
Chloride (mg/L)	*	23	23	21	22	16	36	12	4	4	6	4	4	1	1
Sulfate (mg/L)	*	2300	5570	1600	2720	3540	5980	1230	385	386	229	243	245	26	16
Bicarbonate (mg/L)	*	227	409	278	339	627	951	792	605	601	325	401	443	358	263
Ammonia (mg/L)	*	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Calcium (mg/L)	*	396	508	238	388	220	224	114	89	92	62	68	81	61	54
Magnesium (mg/L)	*	226	520	184	338	525	977	251	120	125	70	84	82	40	30
Potassium (mg/L)	*	17	26	10	10	26	46	21	10	11	8	12	12	5	5
Sodium (mg/L)	*	389	1390	280	349	662	1180	316	71	76	47	50	49	9	4

* dry site

APPENDIX G

FISH SURVEY RESULTS FROM HISTORICAL COMPARISONS

APPENDIX G. Species collected at historical treatment and control sites during summers of 1994 and 2006.
(* = dry site, ** = no species number reported)

	Big Goose Creek				Clear Creek			
	A		B		A		B	
Family	1994	2006	1994	2006	1994	2006	1994	2006
Common name, *Genus species*								
Hiodontidae								
goldeye, *Hiodon alosoides*	0	0	0	0	**	0	10	5
Cyprinidae								
lake chub, *Couesius plumbeus*	1	0	0	0	0	0	0	0
common carp, *Cyprinus carpio*	3	1	0	0	0	2	2	2
western silvery minnow, *Hybognathus argyritis*	0	0	0	0	0	0	0	0
brassy minnow, *Hybognathus hankinsoni*	0	0	0	0	2	0	3	0
plains minnow, *Hybognathus placitus*		0	0	0	1	0	0	0
sturgeon chub, *Macrhybopsis gelida*	0	0	0	0	0	0	0	0
spottail shiner, *Notropis hudsonius*	0	0	0	0	0	0	0	0
sand shiner, *Notropis stramineus*	0	0	0	0	15	154	0	3
fathead minnow, *Pimephales promelas*	0	17	0	0	1	0	3	0
flathead chub, *Platygobio gracilis*	0	0	0	0	28	32	56	0
longnose dace, *Rhinichthys cataractae*	110	0	416	1	73	0	54	0
creek chub, *Semotilus atromaculatus*	0	0	0	0	4	0	0	0
Catostomidae								
river carpsucker, *Carpoides carpio*	0	0	0	0	0	0	2	1
longnose sucker, *Catostomus catostomus*	4	2	12	5	0	3	3	0
white sucker, *Catostomus commersonii*	3	0	48	0	20	2	7	1
mountain sucker, *Catostomus platyrhynchus*	5	0	33	0	0	0	0	0
shorthead redhorse, *Moxostoma macrolepidotum*	1	2	0	0	10	0	10	5
Ictaluridae								
black bullhead, *Ameiurus melas*	0	0	**	0	0	0	0	0
channel catfish, *Ictalurus punctatus*	0	0	0	0	0	1	0	6
stonecat, *Noturus flavus*	0	1	1	0	5	0	9	0
Cyprinodontidae								
northern plains killifish, *Fundulus kansae*	0	0	0	0	0	0	0	0
Centrarchidae								
rock bass, *Amblopites rupestris*	56	114	3	90	1	5	18	12
smallmouth bass, *Micropterus dolomieu*	0	24	0	0	0	2	3	7
largemouth bass, *Micropterus salmoides*	0	0	0	0	0	0	0	0
green sunfish, *Lepomis cyanellus*	0	0	0	0	0	0	0	0
Salmonidae								
brown trout, *Salmo trutta*	0	0	0	0	0	0	0	0

APPENDIX G.—Extended.

	Clear Creek				Crazy Woman Creek			
	D		E		A		B	
	1994	2006	1994	2006	1994	2006	1994	2006
Family								
Common name, *Genus species*								
Hiodontidae								
goldeye, *Hiodon alosoides*	0	0	0	0	2	*	1	0
Cyprinidae								
lake chub, *Couesius plumbeus*	0	0	0	0	0	*	0	0
common carp, *Cyprinus carpio*	0	0	0	1	4	*	3	0
western silvery minnow, *Hybognathus argyritis*	0	0	0	0	0	*	0	0
brassy minnow, *Hybognathus hankinsoni*	0	0	0	0	0	*	0	0
plains minnow, *Hybognathus placitus*	0	0	0	0	0	*	0	0
sturgeon chub, *Macrhybopsis gelida*	0	0	0	0	1	*	0	0
spottail shiner, *Notropis hudsonius*	0	0	0	0	0	*	0	0
sand shiner, *Notropis stramineus*	0	0	0	0	15	*	1	75
fathead minnow, *Pimephales promelas*	0	0	**	0	0	*	0	0
flathead chub, *Platygobio gracilis*	0	0	0	0	103	*	12	12
longnose dace, *Rhinichthys cataractae*	55	5	33	6	74	*	59	443
creek chub, *Semotilus atromaculatus*	7	5	1	68	0	*	0	0
Catostomidae								
river carpsucker, *Carpoides carpio*	0	0	0	0	2	*	1	0
longnose sucker, *Catostomus catostomus*	0	0	0	29	0	*	0	0
white sucker, *Catostomus commersonii*	8	11	**	0	3	*	**	161
mountain sucker, *Catostomus platyrhynchus*	0	0	0	0	1	*	0	0
shorthead redhorse, *Moxostoma macrolepidotum*	0	1	0	0	1	*	0	0
Ictaluridae								
black bullhead, *Ameiurus melas*	0	0	0	0	0	*	0	0
channel catfish, *Ictalurus punctatus*	0	0	0	0	2	*	0	0
stonecat, *Noturus flavus*	3	0	0	0	1	*	6	2
Cyprinodontidae								
plains killifish, *Fundulus kansae*	0	0	0	0	0	*	0	0
Centrarchidae								
rock bass, *Amblopites rupestris*	6	11	1	50	0	*	0	0
smallmouth bass, *Micropterus dolomieu*	0	0	0	0	0	*	0	0
largemouth bass, *Micropterus salmoides*	0	0	0	0	0	*	0	0
green sunfish, *Lepomis cyanellus*	0	0	0	0	0	*	0	0
Salmonidae								
brown trout, *Salmo trutta*	0	0	0	0	0	*	0	0

APPENDIX G.—Extended.

	Crazy Woman Creek						Little Goose Creek	
	C		D		E		A	
	1994	2006	1994	2006	1994	2006	1994	2006
Family								
Common name, *Genus species*								
Hiodontidae								
goldeye, *Hiodon alosoides*	2	1	1	0	4	0	0	0
Cyprinidae								
lake chub, *Couesius plumbeus*	0	0	0	0	0	0	0	0
common carp, *Cyprinus carpio*	0	27	3	34	2	15	1	0
western silvery minnow, *Hybognathus argyritis*	0	0	0	0	0	0	0	0
brassy minnow, *Hybognathus hankinsoni*	0	0	0	0	0	0	0	0
plains minnow, *Hybognathus placitus*	0	0	0	0	0	0	0	0
sturgeon chub, *Macrhybopsis gelida*	0	0	0	0	0	0	0	0
spottail shiner, *Notropis hudsonius*	0	0	0	0	0	0	0	0
sand shiner, *Notropis stramineus*	6	633	0	498	1	216	0	0
fathead minnow, *Pimephales promelas*	1	4	0	0	3	0	0	31
flathead chub, *Platygobio gracilis*	7	10	20	18	10	6	0	0
longnose dace, *Rhinichthys cataractae*	57	64	34	54	147	10	276	465
creek chub, *Semotilus atromaculatus*	0	0	0	0	0	0	0	0
Catostomidae								
river carpsucker, *Carpoides carpio*	5	0	0	0	0	0	0	0
longnose sucker, *Catostomus catostomus*	0	0	0	0	4	0	6	100
white sucker, *Catostomus commersonii*	0	434	4	93	3	8	114	208
mountain sucker, *Catostomus platyrhynchus*	0	0	1	2	0	0	24	33
shorthead redhorse, *Moxostoma macrolepidotum*	1	5	1	0	5	0	0	0
Ictaluridae								
black bullhead, *Ameiurus melas*	0	116	0	79	0	1	0	0
channel catfish, *Ictalurus punctatus*	1	2	0	1	0	0	0	0
stonecat, *Noturus flavus*	0	0	1	3	9	2	0	0
Cyprinodontidae								
plains killifish, *Fundulus kansae*	0	0	0	0	0	0	0	0
Centrarchidae								
rock bass, *Amblopites rupestris*	0	0	0	0	0	0	11	0
smallmouth bass, *Micropterus dolomieu*	0	0	0	1	0	15	0	0
largemouth bass, *Micropterus salmoides*	0	0	0	0	0	0	0	8
green sunfish, *Lepomis cyanellus*	0	0	0	0	0	0	0	0
Salmonidae								
brown trout, *Salmo trutta*	0	0	0	0	0	0	0	2

APPENDIX G.—Extended.

	Little Powder River							
	A		B		C		D	
	1994	2006	1994	2006	1994	2006	1994	2006
Family								
Common name, *Genus species*								
Hiodontidae								
goldeye, *Hiodon alosoides*	**	0	**	*	**	0	0	0
Cyprinidae								
lake chub, *Couesius plumbeus*	0	0	0	*	0	0	0	0
common carp, *Cyprinus carpio*	0	0	1	*	0	1	0	0
western silvery minnow, *Hybognathus argyritis*	**	0	0	*	0	0	0	0
brassy minnow, *Hybognathus hankinsoni*	0	0	0	*	0	0	0	0
plains minnow, *Hybognathus placitus*	0	0	0	*	0	0	6	0
sturgeon chub, *Macrhybopsis gelida*	0	0	0	*	0	0	0	0
spottail shiner, *Notropis hudsonius*	0	0	0	*	0	0	0	0
sand shiner, *Notropis stramineus*	5	245	15	*	20	157	16	0
fathead minnow, *Pimephales promelas*	1	4	28	*	8	5	19	10
flathead chub, *Platygobio gracilis*	1	4	0	*	1	1	0	0
longnose dace, *Rhinichthys cataractae*	8	47	2	*	5	3	2	0
creek chub, *Semotilus atromaculatus*	0	0	0	*	0	0	0	0
Catostomidae								
river carpsucker, *Carpoides carpio*	0	0	0	*	0	0	0	0
longnose sucker, *Catostomus catostomus*	0	0	0	*	0	0	0	0
white sucker, *Catostomus commersonii*	**	2	7	*	**	5	4	5
mountain sucker, *Catostomus platyrhynchus*	0	0	0	*	0	0	0	0
shorthead redhorse, *Moxostoma macrolepidotum*	0	6	0	*	1	1	0	0
Ictaluridae								
black bullhead, *Ameiurus melas*	0	0	0	*	0	2	0	1
channel catfish, *Ictalurus punctatus*	0	3	0	*	0	5	0	0
stonecat, *Noturus flavus*	**	5	**	*	**	2	**	1
Cyprinodontidae								
plains killifish, *Fundulus kansae*	0	0	0	*	0	0	0	0
Centrarchidae								
rock bass, *Amblopites rupestris*	0	0	0	*	0	0	0	0
smallmouth bass, *Micropterus dolomieu*	0	0	0	*	0	0	0	0
largemouth bass, *Micropterus salmoides*	0	0	0	*	0	0	0	0
green sunfish, *Lepomis cyanellus*	0	1	4	*	3	0	0	0
Salmonidae								
brown trout, *Salmo trutta*	0	0	0	*	0	0	0	0

APPENDIX G.—Extended.

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	Little Powder River		Prairie Dog Creek				Salt Creek	
	E		A		B		A	
	1994	2006	1994	2006	1994	2006	1994	2006
Family								
Common name, *Genus species*								
Hiodontidae								
goldeye, *Hiodon alosoides*	0	*	0	0	0	0	0	0
Cyprinidae								
lake chub, *Couesius plumbeus*	0	*	0	0	0	0	0	0
common carp, *Cyprinus carpio*	0	*	6	2	0	0	0	0
western silvery minnow, *Hybognathus argyritis*	0	*	0	0	0	0	0	0
brassy minnow, *Hybognathus hankinsoni*	0	*	0	0	0	0	0	0
plains minnow, *Hybognathus placitus*	0	*	0	0	0	0	45	0
sturgeon chub, *Macrhybopsis gelida*	0	*	0	0	0	0	0	0
spottail shiner, *Notropis hudsonius*	0	*	0	6	0	0	0	0
sand shiner, *Notropis stramineus*	0	*	0	0	0	0	220	666
fathead minnow, *Pimephales promelas*	156	*	1	0	3	2	4	0
flathead chub, *Platygobio gracilis*	0	*	19	0	19	27	93	66
longnose dace, *Rhinichthys cataractae*	0	*	22	1	22	140	28	8
creek chub, *Semotilus atromaculatus*	0	*	13	52	76	140	0	0
Catostomidae								
river carpsucker, *Carpoides carpio*	0	*	0	0	0	0	0	1
longnose sucker, *Catostomus catostomus*	0	*	1	0	1	0	0	0
white sucker, *Catostomus commersonii*	9	*	38	98	49	49	2	0
mountain sucker, *Catostomus platyrhynchus*	0	*	5	4	0	26	0	1
shorthead redhorse, *Moxostoma macrolepidotum*	0	*	0	0	0	0	0	0
Ictaluridae								
black bullhead, *Ameiurus melas*	0	*	0	0	0	0	0	0
channel catfish, *Ictalurus punctatus*	0	*	0	0	0	0	0	0
stonecat, *Noturus flavus*	0	*	23	0	0	0	0	0
Cyprinodontidae								
plains killifish, *Fundulus kansae*	0	*	0	0	0	0	0	84
Centrarchidae								
rock bass, *Amblopites rupestris*	0	*	2	0	0	0	0	0
smallmouth bass, *Micropterus dolomieu*	0	*	0	0	0	0	0	0
largemouth bass, *Micropterus salmoides*	0	*	0	0	0	0	0	0
green sunfish, *Lepomis cyanellus*	0	*	0	0	0	0	0	0
Salmonidae								
brown trout, *Salmo trutta*	0	*	0	0	0	0	0	0

APPENDIX H

WATER QUALITY RESULTS FROM HISTORICAL COMPARISONS

APPENDIX H.—Field and laboratory water quality results from 2006 for historical treatment and control streams.

	Big Goose Creek		Clear Creek				Crazy Woman Creek				
	A	B	A	B	D	E	A	B	C	D	E
Field values											
Conductivity (umhos/cm)	814	521	1780	1321	826	770	*	3191	6650	2967	2807
Dissolved oxygen (mg/L)	8.54	9.55	7.36	8.55	9.63	5.69	*	3.58	5.69	5	7.41
Temperature (°C)	20.1	24.7	21.4	26.8	22.1	19.5	*	21.6	22.5	20.3	25.7
pH	8.6	9.1	8.6	8.7	8.9	8.4	*	8.7	8.4	8.5	8.7
Turbidity (NTU)	6	2	13	10	4	5	*	63	34	11	30
Lab values											
pH	9	8	8	8	8	8	*	8	8	8	8
Conductivity (umhos/cm)	816	596	2000	1620	2880	896	*	4100	8880	3240	4470
Total dissolved solids (mg/L)	498	360	1550	1260	2440	609	*	3800	8760	2840	4270
Alkalinity (mg/L)	252	202	183	145	342	167	*	186	335	228	278
Chloride (mg/L)	15	2	6	4	11	7	*	23	23	21	22
Sulfate (mg/L)	162	106	832	764	1400	289	*	2300	5570	1600	2720
Bicarbonate (mg/L)	289	242	224	174	417	190	*	227	409	278	339
Ammonia (mg/L)	0	0	0	0	0	0	*	0	0	0	0
Calcium (mg/L)	66	58	141	131	280	75	*	396	508	238	388
Magnesium (mg/L)	49	32	93	82	126	36	*	226	520	184	338
Potassium (mg/L)	5	3	9	8	6	4	*	17	26	10	10
Sodium (mg/L)	36	21	152	101	230	55	*	389	1390	280	349

* dry site

APPENDIX H.—Extended

	Little Goose Creek	Little Powder River					Prairie Dog Creek		Salt Creek
	A	A	B	C	D	E	A	B	A
Field values									
Conductivity (umhos/cm)	388	3095	*	2543	2610	*	2235	1808	6130
Dissolved oxygen (mg/L)	8.12	6.02	*	6.13	6.5	*	7.4	6.59	7.37
Temperature (°C)	25.3	21.6	*	19.6	24.7	*	24.2	22	20.4
pH	8.5	8.4	*	8.4	8.7	*	8.5	8.4	9
Turbidity (NTU)	11	130	*	260	95	*	11	38	52
Lab values									
pH	8	8	*	8	7	*	8	8	8
Conductivity (umhos/cm)	658	1370	*	1370	457	*	2550	1980	6030
Total dissolved solids (mg/L)	392	946	*	968	644	*	2010	1540	3780
Alkalinity (mg/L)	246	173	*	169	65	*	375	405	147
Chloride (mg/L)	5	27	*	10	4	*	9	5	1130
Sulfate (mg/L)	91	413	*	441	132	*	1110	750	1140
Bicarbonate (mg/L)	300	212	*	206	79	*	457	495	176
Ammonia (mg/L)	0	0	*	0	0	*	0	0	0
Calcium (mg/L)	59	83	*	71	25	*	185	176	126
Magnesium (mg/L)	41	33	*	31	7	*	151	114	55
Potassium (mg/L)	3	18	*	14	9	*	14	11	39
Sodium (mg/L)	20	144	*	175	64	*	218	135	1130

* dry site

APPENDIX I

PRAIRIE STREAM SURVEY PROTOCOL

Fish and Habitat Sampling Protocol for Prairie Streams

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1. ***Site location***.-Locate the sampling site using GPS for random sites, or by convenience for non-random sites. The GPS location will be the center of the reach, this is where you place the "F" flag (see Step 2). If the site is dry, shift the reach up or downstream to capture the most wetted channel possible on the parcel of land where you have permission for sampling.
2. ***Laying out the sample reach***.-Lay out a 300 m sample reach using a measuring tape and a set of 11 pin flags (labeled A-K). Follow the curves in the stream channel with the measuring tape; do not cut across curves. To avoid spooking fish, walk along the bank, not in the stream. Place a flag every 30 m. The "A" flag will be at the downstream end, the "K" flag will be at the upstream end of the reach. The "F" flag will go in the center of the reach.
3. ***Block nets***.-Place block nets (these can be old seines, 1/4" mesh) at the upstream (K flag) and downstream (A flag) ends of the sample reach if the water in the channel is continuous, deeper than 25 cm, and relatively clear. This prevents fish from leaving the sample reach.
4. ***Seining***.-Select the seine based on the size of the stream to be sampled. The seine length to be used should be approximately equal to or slightly greater than the stream width, and the seine height should be about 1.5 to 2 times greater than the depth of the stream. Dip nets can be used in very shallow, small habitats. Seining begins at the upstream end (K flag) and proceeds downstream to the A flag. Seining is performed by two people, one on each end of the seine. In pools, the seine is pulled down the stream channel, using the shore and other natural habitat features as barriers. Begin with the seine rolled up on each seine braille. The seine is typically set perpendicular to shore and hauled downstream parallel to shore. As you proceed, let out enough seine so that the seine forms a "U" shape, but not so much that the net

is hard to control. Adjust the length of the seine by rolling or un-rolling net on the seine braille. The speed of seining should be fast enough to maintain the “U” shape, but not so fast that the floats become submerged, or that the seine’s lead line come way up off the bottom of the stream. If rocks or other snags are on the bottom, the seine can be lifted off the bottom for a moment to avoid the snag, or one of the netters can bring the seine around the snag to avoid it, all the while maintaining the forward progress of the seine. Similarly, areas of dense aquatic vegetation can be avoided. It is important not to stop the forward progress, because fish will swim out of the seine. It is better to avoid a snag while keeping moving than to become snagged, which will allow fish to escape. In “snaggy” waters, keep more of your seine rolled up for better control.

Proceed downstream while seining. In narrow streams, the entire channel width is spanned with the seine. In wider streams, one person walks along the shore, while the other wades through the channel. The length of each seine haul will depend on the natural features of the stream channel and shoreline, but seine hauls should not normally be more than 60 or 90 m long. Side channel bars or the end of a standing pool are good areas to haul out or “beach” the seine. Where a large bar or end of a standing pool is present both netters can simply run the net up on the shore. In streams with steep banks or lack of obvious seine beaching areas the “snap” technique can be used. At the end of the haul, the person near shore stops, while the person farthest out turns into shore, quickly, until the seine is up against the bank. The two netters then walk away from each other, taking the slack out of the seine, and keeping the seine’s lead line up against the bank.

In riffles, with moderate to fast current, the “kick seine” technique can be used. The seine is held stationary in a “U” shape, while the other team member disturbs the substrate immediately upstream of the net. Then the net is quickly “snapped” out of the water by both team members using an upstream scooping motion.

Seine the entire 300 m reach, covering the linear distance at least once. If part of the 300 m is dry, just skip it. If the stream is much wider than your seine, do extra seine hauls in the large pools to cover the extra width. Sample all habitat types (shoreline, thalweg, side channels, backwaters).

After each seine haul, place fish in a bucket. If the water is warm, or you have captured many fish, place fish in a fish bag to keep them alive until seining is completed, or use an aerator. If you have to work up fish before seining is completed, release processed fish in an area that has already been seined, as far away from the area remaining to be seined as possible (or outside of the block nets). Large fish such as northern pike, common carp, white sucker, shorthead redhorse, or channel catfish, can be measured, given a small clip to the lower caudal fin and released immediately. Marking fish will prevent them from being counted more than once if they are captured again.

5. ***Processing captured fish***.-Record the species of each fish captured, and measure 20 “randomly” selected fish to the nearest millimeter, total length. If the species of fish is unknown, try to at least record it as Unknown type 1, Unknown type 2, etc. Keep track of and record the minimum and maximum length of each species.

   For each species, preserve a subsample of at least 10 individuals per site to serve as voucher specimens. Record a small letter “v” next to the recorded length of the fish that is vouchered to allow for later validation. For *Hybognathus* spp., voucher up to 20 individuals per site. Kill the fish to be vouchered by placing them in a small bucket or 1000 ml nalgene jar with an overdose solution of MS-222. After fish processing is completed, drain the MS-222 solution and place the fish in a 1000 ml nalgene jar with a 10% solution of formalin (in clear water, if possible). For specimens longer than 150 mm, an incision should be made on the right ventral side of the abdomen after death, to allow fixative to enter the body cavity. The volume of formalin solution should be approximately equal to the twice the volume of fish tissue to be preserved, and the fish volume should be considered water when concentrations are determined. For example, if the fish take up 250 ml of the 1000 ml volume, you need about 500 ml of 10 % formalin solution (75 ml formalin and 425 ml water) in the 1000 ml nalgene jar. If necessary, use a second jar to accommodate all of the specimens. Use safety glasses and gloves when pouring formalin. Do not let the fish "cook" in the sun for a while and preserve them later, do it as soon as possible. Label all jars inside and out with Site, Site Number, Lat/Long, Date, Collectors names. Use pencil on Write-In-the-Rain or high rag paper for inside labels (just put the label right in with the fish), use a sticker label on the outside, cover it with clear (ScotchPad high performance packing tape pad 3750-P). Fish specimens should be left in formalin solution for at least 2-7 days. Fish specimens must have formalin solution soaked out before being handled extensively. Specimens should be soaked in water for at least 2 days, and water should be changed at least four times during this period. After soaking out the formalin, the fish specimens should be placed in either 70% ethanol or 40% isopropanol for long-term storage.

6. ***Habitat survey***.-Channel width, depth of water, and substrate will be measured at 11 transects perpendicular to the stream channel (located at Flags A-K), and along the thalweg in 10 thalweg intervals between transects (deepest part of channel). Stream width is measured to the nearest 0.1 m, depth is measured to the nearest cm, and substrate sizes and codes are on the data sheet. One person will be in the stream taking measurements while the other records data. Record the Latitude and Longitude (in digital degrees) of the F flag, the stream name, site number, the date, the flow status (flowing, continuous standing water, or interrupted standing water) and the names of the crew members on the data sheet. Take photographs of the site, capturing as much of the sampling reach as possible. Make sure the date feature on the camera is turned on, to allow for later identification of site photographs.

Transects.-Start on the left bank (facing downstream) at Flag A. Measure and record the wetted width of the channel to the nearest 0.1 m. Measure and record (separated by a comma on the data sheet) five equally spaced depth and substrate measurements across the wetted stream channel:

1. Left Bank-5 cm from the left bank;
2. Left Center-halfway between the Center and the Left Bank;
3. Center-center of the wetted stream;
4. Right Center-halfway between the Center and the Right Bank;
5. Right Bank-5 cm from the right bank

Thalweg.-Begin by recording the depth and substrate 3 m upstream of the transect, in the deepest part of the channel (thalweg). Proceed up the thalweg to Flag B, recording depth and substrate every 3 m along the thalweg. You will record a total of 10 depths and substrates between each pair of transects. If the stream channel is dry, record a 0 for depth, and record the substrate. The last thalweg measurement point should fall on the next upstream transect. The 3 m interval can be estimated, and it is helpful if the data recorder helps to keep the person in the stream from "squeezing" or "stretching" the thalweg measurements.

Repeat this procedure until all 11 transects and 10 thalweg intervals are completed.